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Unlocking the potential of critical minerals extraction for Africa's structural transformation

Lingfei Weng[1]

Abstract: There have been debates for centuries on whether extractive industries have brought resource curses or blessings to African countries. Some minerals, such as lithium, copper, and cobalt, have emerged as critical to the clean energy transition. Who and how to harness them will determine whether African countries rich in critical minerals can transform their economies into more productive structures. In this paper, critical minerals are first defined from a structural transformation perspective, followed by a comprehensive review of critical minerals extraction driven by clean energy technologies in Africa. It argues that the criticality of minerals changes over time, and technological innovation is adding to the uncertainty of future demand for critical minerals. Developing industrial capabilities by harnessing critical minerals is essential for African countries to eradicate poverty and enhance their social-economic prosperity. Rethinking structural transformation beyond an economic-centred framework might inspire policy imagination for Africa to escape the resource tragedy.

Keywords: Critical minerals; structural transformation; clean energy technologies; challenges and implications; Africa

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1. Introduction

Demand for critical minerals is set to expand significantly, mainly driven by the burgeoning requirements of the clean energy sector. Critical minerals such as copper, lithium, nickel, cobalt, graphite and rare earth elements are essential in many of today's rapidly growing clean energy technologies - from wind turbines and electricity networks to electric vehicles. The World Bank estimates that the proliferation of clean energy technologies could lead to a nearly 500% increase in demand for minerals such as graphite, lithium, and cobalt by 2050. The market size for key minerals could top $400 billion by value (World Bank, 2020). Unlocking the potential of critical minerals for energy transition could bring new revenue opportunities for the industry, create jobs for society, and help transform economic structures to reach net zero emission by 2050. Therefore, critical minerals, which used to be a small market segment, are now moving to center stage in the mining industry.

Africa is estimated to hold about 30 percent of the world's proven critical mineral reserves. A strong global demand for commodities set off a mining boom in Africa in the first decade of the 21st century, as metal and oil prices almost tripled, largely driven by the rapid economic growth of emerging economies. Fuel and metals accounted for more than 60 percent of the region's total exports in 2014, compared with 16 percent for manufactured goods. Africa's pattern of exporting raw materials rather than manufactured goods makes it particularly vulnerable to the volatility of commodity prices. Critical minerals-rich countries will have a 20-to-30-year window to tap into expected investment flows to generate long-term economic development. Many expect that the new boom in commodities, such as copper and cobalt, will revive Africa's waning manufacturing industry. Investment in energy transition sectors can accelerate economic diversification and drive a shift from dominant resource-based economies towards an industries-based economic structure. Thus, critical minerals and implementing clean energy technologies present practical opportunities to cultivate a growing industrial base for Africa (IEA, 2024a).

Developing productive capacity has become increasingly recognized as needed to foster structural transformation, particularly for African countries. A growing awareness raised from academic studies, international agencies, and African governments is that there is an opportunity for Africa to leverage the demand for critical minerals to cultivate a growing industrial base and transform their economies into a productive structure. However, currently, critical minerals are the focus of much international dialogue, diplomacy, and geopolitical rivalry, such as between Western economies and China; there is a lack of empirical evidence to analyze the implications of critical minerals for Africa's structural transformation and industrialization. As African countries missed past chances for the industrial revolution, can they catch up now by unlocking the potential of critical minerals and leveraging this new opportunity for their structural transformation? If so, how?

2. What are critical minerals and how do they matter?

2.1 Critical to whom?

When we speak of critical minerals, we need to understand to whom and in what use they are critical - is it critical to the investors of mining industries, owners of mining firms, the countries that own minerals, or those countries/companies seeking minerals? This is a key question for defining critical minerals, as it situates the question in a specific context - each stakeholder will have different interests regarding what is to be evaluated.

Minerals are critical for many countries as they recognize the strategic importance of mineral supply chains and are compiling national critical material strategies. Each country or region has indicators regarding those minerals that are classified as 'critical' - indicators for national security, economic structural transition, and geopolitical strategy (Hayes and McCullough, 2018). For countries dependent on mineral imports, such as the US, EU, and South Korea, the primary objective is to anticipate and offset potential supply risks. For example, the US has announced its list of critical minerals, emphasizing supply risk through natural hazards or human-made disruptions, trade exposure, and economic vulnerability (Kelley et al., 2021). In contrast, mineral-rich countries such as Australia and Canada seek to boost the competitiveness of their mining sectors and attract investments (IRENA, 2023).

Apart from the strategic consideration of national interests, there is a geopolitical concern about the vulnerability of critical mineral supply chains. The Russian invasion of Ukraine and China's dominant role in producing critical minerals have raised concerns for advanced economies that rely mainly on imports of critical minerals from both countries (Centre for Strategic and International Studies, 2024). In other words, who controls the supply chain of will have a decisive impact on what minerals are critical to whom. Assessing the vulnerability of supply chains requires identifying the parties with substantial control over the producers of critical minerals. Studies have revealed that the extent of control by entities from China, Europe, and the US, among others, over the supply chains of critical minerals is distinct from the control associated with the location of production (Leruth et al., 2022). For example, Democratic Republic of the Congo (DRC) is by far the largest producer of cobalt. Although 69 percent of cobalt production originates in the DRC, firms incorporated there only account for 3.5 percent of global output. The top producers are incorporated in the UK, Switzerland and China, accounting for 41.7%.

Unlike cobalt, the copper market is not concentrated geographically. Chile is the world's top producer of copper, followed by Peru and China. Regarding the top producing firms, UK companies are collectively the largest producers, followed by firms incorporated in Chile, the US and Mexico. Nevertheless, by controlling several mining firms, China controls the largest share of copper production but only occupies a small share of incorporated firms (11.2%) (Leruth et al., 2022). The number of countries that incorporated companies extracting nickel is greater than the number of countries producing nickel. Indonesia has the largest reserves and is the world's leading nickel producer, but foreign companies extract 80% of it. Companies from Brazil, Russia, China and the Philippines control global nickel production (Ericsson et al., 2020).

The picture is even more complicated when looking at the countries that own critical mineral reserves. Africa accounts for much of the global reserves of minerals critical to the production of low-carbon technologies, creating opportunities to diversify the mining and processing of these minerals (Zero Carbon Analytics, 2024). The dominance of China in the critical minerals supply chain poses geopolitical and mineral security threats to Western countries, who are now shifting attention to African countries, playing catchup as geopolitical rivalries driven by energy security intensify around the supply of critical minerals (Andreoni and Robert, 2022). As the continent is less industrialized than others, most African countries do not process their own critical minerals, nor do they attract companies in the midstream or downstream of the value chain (Müller, 2023). It has been debated for decades whether minerals bring African countries rich in resources a curse or a blessing (Auty and Warhurst, 1993; Auty, 2004). The underlying rationale for who benefits and how they benefit from mineral resources is understudied.

2.2 Factors to consider in defining the 'criticality' of minerals

Mineral criticality is a subjective concept that has evolved over time. The modern conceptualization of critical elements emerged in the United States before WWI (Hayes and McCullough, 2018). It was formalized by the passage of the Strategic and Critical Materials Stockpiling Act in 1939 as it related to defense preparedness (Schulz et al., 2017). Since the 1980s, the criticality conversation has shifted to emphasize low-volume elements that produce high-technology goods, clean energy and defense applications.

The first study to define mineral criticality and to suggest how it might be measured was a report released in 2008 by the United States (US) National Research Council (National Research Council, 2008). It was based on approximations and expert judgment of 11 metals and groups of metals. It used two parameters to determine criticality: the supply risk (or likelihood of supply disruption) and the impact of supply disruption (or vulnerability). Another subsequent assessment, carried out by the European Union (EU) (European Commission, 2010), adopted a broadly similar approach, applying it to a much more comprehensive range of materials and employing quantitative data to estimate two dimensions of criticality: (a) they are essential for the functioning of modern technologies, economies, or national security, (b) there is a risk that their supply chains could be disrupted.

In the following decade, a proliferation of literature has defined the modern criticality paradigm. The studies in this literature vary significantly in scope, purpose, and methodology, depending on who asks the question, for what purpose, and over what timescale (Zepf et al., 2014). They have been undertaken by governments, non-governmental organizations, academics, commercial companies, and private corporations (Hofmann et al., 2018). Some have assessed many materials, others only related to a particular industry or sector. Some have been global in scope, while others have focused on countries or regions. For example, the frame of reference of a photovoltaic manufacturer may be dramatically different from that of a governmental defense agency (Fortier et al., 2015). For another example, Europe, the US, and Australia classified some minerals as 'critical' because they are essential to transitioning to a low carbon economy or national security, have no viable substitutes, and are vulnerable to supply chain disruption (Renneboog et al., 2022).

Debates and consensus regarding 'criticality' have sparked the formulation of a complex critical materials agenda dictated not only by industrial concerns but also reflecting perceived state interests of economic, geopolitical, and technological conditions in a changing global power environment (Hayes and McCullough, 2018). Where data are lacking or unreliable, expert judgment is often elicited to provide qualitative estimates for the relevant metrics. As a result, many lists of critical minerals have been produced based on the evaluators' perspective, although none should be considered fixed or correct (Grandell et al., 2016).

2.3 How do critical minerals matter?

Record deployment of clean energy technologies propels unprecedented demand for critical minerals (IRENA, 2023). For example, building solar photovoltaic (PV) plants, wind farms, and electric vehicles (EVs) generally requires more minerals than their fossil fuel-based counterparts (IEA, 2021). A typical electric car requires six times the mineral inputs of an internal combustion car, and a wind plant requires nine times more mineral resources than a gas-fired power plant. Furthermore, lithium, nickel, cobalt, manganese, and graphite are crucial to battery performance, longevity, and energy density. Rare earth elements are essential for permanent magnets for wind turbines and EV motors. Electricity networks need a lot of copper and aluminum, with copper being a cornerstone for all electricity-related technologies (IEA, 2024b).

Critical minerals are the foundation on which clean energy technology is built. The availability of critical mineral supplies will heavily influence the affordability and speed of energy transitions (Brown, 2018). Simply put, there is no green energy transition without critical minerals, which is why their supply chain resilience is an increasing priority for advanced economies (IEA, 2024a). Many critical materials have a range of applications in various industrial sectors, including clean energy, digitalization, and defense and aerospace application sectors. There will be increasing competition between all sectors for the same critical minerals, metals, processed materials, and components (European Commission, 2020). This applies to critical raw materials such as gallium, indium, rare earths, cobalt, niobium and silicon.

Africa has a historic opportunity to unleash a wave of structural transformation by leveraging their endowed critical minerals and rare metals (UNCTAD, 2024). Global demand for critical minerals largely driven by energy transition presents practical opportunities to cultivate a growing industrial base for Africa (Hine et al., 2023). If Africa is to truly benefit from the critical minerals boom, it will require an agenda placing its own development needs in the center, embracing integrated strategies that involve governments, the private sector, civil society, and grassroots organizations in mining governance, ensuring that the social and economic benefits of critical mineral extraction are equitably shared among local communities (Weng et al., 2013).

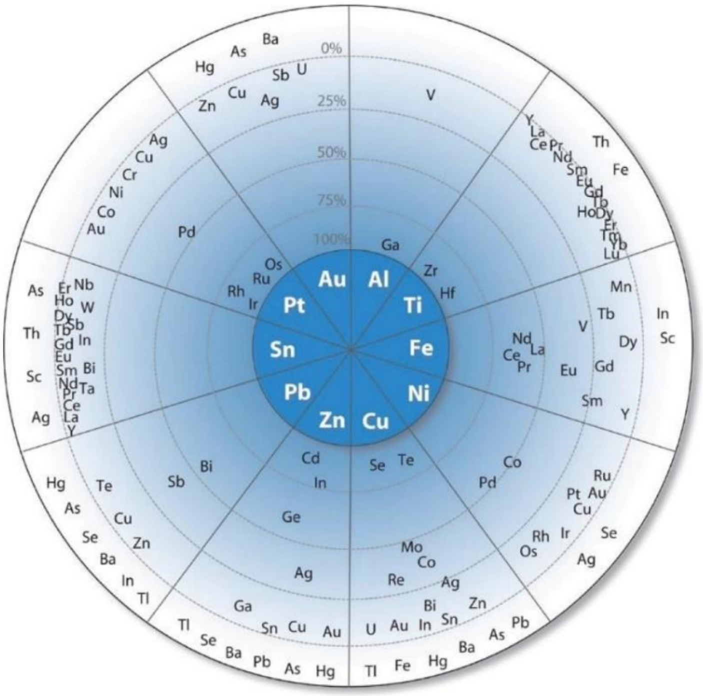
2.4 Defining the critical minerals in this study

2.4.1 Critical minerals extraction for technical application

There are over 4,000 different minerals, many of which contain metallic elements. Minerals are solid, naturally occurring inorganic substances in the Earth's crust, classified based on crystal form and chemistry (Josso et al., 2021). In general, minerals are divided into two types, namely metallic and non-metallic. Metallic minerals are divided further into ferrous and non-ferrous metallic minerals (the difference between them is whether they contain iron or not), such as manganese, iron ore and bauxite. Industrial minerals are non-metallic and non-fuel mineral resources including gravel, clay, sand (Silica), gypsum, bentonite, and barite. They are increasingly essential to high-tech sectors through the production of wiring and cables, as well as environmentally friendly products and technologies such as wind turbines and photovoltaic panels (Nassar et al., 2015). Precious metals are typically rare, metallic elemental with a high economic value. Currently, there are eight elements listed as precious metals, gold, silver, platinum, palladium, iridium, osmium, rhodium, and ruthenium.

For most of the human history, only a few metals, such as iron, copper, tin, and lead, were in common use. These metals are typically found in relatively high concentrations of one-half weight percent or more in the continental crust and are produced in relatively high volumes (Vesborg et al., 2012). Although these major metals, along with several precious metals, still form the foundation of any developed economy, the growth in technological innovation that has occurred over the past decades has, in part, been possible because an increasing number of minor metals are that used to perform specialized functions (Nassar et al., 2015). As these minor metals are typically found in relatively low concentrations of less than about 0.1, they seldom form viable deposits of their own. Instead, they occur interstitially in the ores of metals with similar physical and chemical properties. These minor metals are thus often recovered only as by-products during the processing of the major metals, so-called 'host metals'.

Minor metals, also known as 'companion metals', are increasingly used in electronic and solar energy applications (gallium, germanium, selenium, indium, and tellurium), as alloying elements in high-temperature applications (cobalt, hafnium, and rhenium), and several rare earth elements (praseodymium, neodymium, terbium, dysprosium, and lutetium) are important in offshore wind, lighting, and medical imaging (USGS, 2022). As shown in Figure 1, the principal host metals form the inner circle, companion elements appear in the outer circle at distances proportional to the percentage of their primary production (from 100 to 0%) that originates with the host metal indicated (Figure 1). The companion elements in the white region of the outer circle are elements for which the percentage of their production that originates with the host metal indicated has not been determined.



Al: Aluminium
Ti: Titanium
Fe: Iron
Ni: Nickel
Cu: Copper
Zn: Zinc
Pb: Lead
Sn: Tin
Pt: Platinum
Au: Gold
Bi: Bismuth
Cd: Cadmium
Ce: Cerium
Co: Cobalt
Ga: Gallium
Ge: Germanium
Hf: Hafnium
In: Indium
Ir: Iridium
La: Lanthanum
Nd: Neodymium
Os: Osmium
Pd: Palladium
Pr: Praseodymium
Rh: Rhodium
Ru: Ruthenium
Se: Selenium
Te: tellurium
Zr: Zirconium

Figure 1. The wheel of metal companionality. Source: Nassar et al., 2015

2.4.2 Critical minerals extraction for Africa's structural transformation

Structural transformation refers to a series of economic and social changes resulting from changes to the processes of production structure (Chang, 1994). These involve notable transitions in employment towards manufacturing and modern industries, new organization of production, technological upgrading, and related changes in social conditions such as urbanization. Critical mineral exploitation remains a crucial aspect of African development and global trade networks, offering opportunities to drive industrial development and structural transformation on the continent, necessitating the creation of horizontal and vertical linkages across sectors. However, those countries rich in critical minerals may have limited incentives to diversify their economic structures, especially when high demand and prices for natural resources reinforce their comparative advantage and specialization. Additionally, Africa is less industrialized and contributes less to global carbon emissions, and there is a low demand for critical minerals in Africa to transition to a low-carbon economy.

Some minerals have emerged as critical in the new wave of global green and digital transition. Who and how to harness the potential of critical minerals, will determine whether developing countries can transform their economic structure and the pace at which, structural transformation occurs. In this study, we define critical minerals from the perspective of structural transformation. From this perspective, whether minerals are critical or not will depend on whether they can foster Africa's structural transformation. In other words, critical minerals are those minerals whose extraction could be utilized to enhance productivity for economic and social changes in Africa in direct and indirect ways:

Directly, (1) the critical minerals can enhance agricultural productivity, considering the highest-productivity sectors tend to be capital-intensive and are thus less able to absorb large numbers of workers; thus, critical minerals could be fertilizers for increasing agricultural production such as phosphate ore minerals that are applied for contemporary agricultural technology innovation, such as the adoption of robotics technology; (2) the critical minerals can increase the dynamism of manufacturing by moving from traditional fossil fuel-dependent industries to green industries. As Africa's growing energy needs will still rely on fossil fuels for some time before a full transition to clean energy technologies, minerals for such transition are essential in meeting different development needs at different development stages, whether they are relatively advanced economies, like South Africa or less developed economies, like Zambia.

Indirectly, revenues generated from mining industries, if distributed properly, (3) the critical minerals industry can enhance labor productivity through physical and human capital investments. This would foster local expertise and increase sustainable employment opportunities. (4) increase investment in public services such as infrastructure, health, and education to generate social welfare. (5) develop innovative resource governance arrangements and strong institutions that accelerate structural change.

3. An overview of critical minerals in Africa

Africa is already a major producer of several minerals and metals classified as critical by the Western world. The growth of the global clean energy sector is expected to continue to drive a high demand for Africa's critical minerals (Müller, 2023; Boafo et al., 2024). The Africa Mining Vision (AMV) was adopted at the African Union (AU) Summit in 2009. The AMV is first and foremost a developmental mining approach that is Africa's response to tackling the paradox of great mineral wealth through building economic and social linkages that benefit Africa itself (African Union, 2009). A key element of the AMV uses mineral resources to catalyze broad-based growth and development needs to maximize the concomitant opportunities offered by a mineral resource endowment, particularly deepening the resources sector through the optimization of linkages along the value chains (Figure 2). That means thinking about how mining can contribute better to local development to ensure communities see real benefits from large-scale industrial mining and that their environment is protected (Müller, 2023).

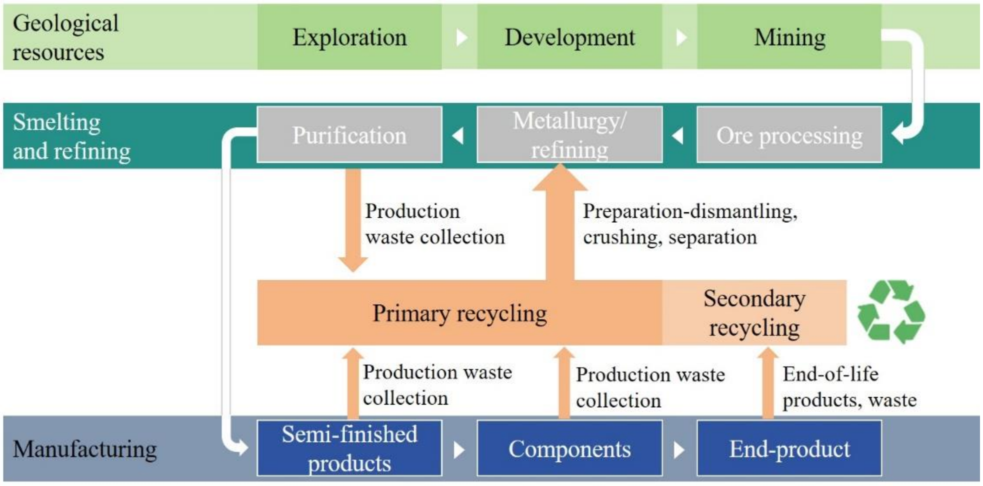


Figure 2. The value chain for critical minerals. Source: IRENA, 2023

Africa's urgent need to industrialize is universally acknowledged. A resource-based African industrialization and development strategy must be rooted in the utilization of Africa's significant resource assets to catalyze diversified industrial development to achieve other long-term goals like poverty reduction. Historical development experiences reveal that in most African countries, the mining sector has played a limited transformative role (Andreoni et al., 2021). The structural transformation of African economies must be an essential component of any long-term strategy to eradicating poverty and underpin sustainable growth and development across the continent (African Union, 2009).

3.1 Critical minerals reserve in Africa

Africa is estimated to hold about 30 percent of the volume of the world's proven critical mineral reserves (UNCTAD, 2024). Global demand for critical minerals highlights Africa's central role in the green energy transition and transformation (Andreoni and Avenyo, 2023). Table 1 illustrates the distribution of selected critical mineral resources across Africa and their shares by global reserves and production (Table 1). For instance, the USGS indicated that DRC, Madagascar, and Morocco have about 50 percent of global reserves and produce about 70 percent of cobalt - a critical mineral essential for battery storage and electric vehicles. The platinum group of metals (PGMs) is critical for abating carbon-intensive and important for green hydrogen. South Africa and Zimbabwe hold about 92 percent of global reserves of platinum, producing about 82 percent globally in 2022. Copper is the only critical mineral present in all the most important clean energy technologies, and DRC is the largest producer of copper in Africa (IEA, 2021, 2024b).

Table 1. Distribution of selected critical minerals in Africa in 2022. Source: Andreoni & Avenyob., 2023; USGS 2024; World Mining Data, 2024

Critical mineral (unit)	Countries	Stock (Reserves)	Total global of reserves (rounded)	Share of global reserves	Mine Production	Total global production (rounded)	Share of global production (%)
Arsenic (metric tons)	Morocco	NA	NA	NA	5450	60100	9.0
Cobalt (metric tons)	DRC	4000000	8300000	48.2	130000	190000	68.4
	Madagascar	100000	8300000	12	3000	190000	1.6
	Morocco	13000	8300000	0.2	2300	190000	1.2
	Zambia	NA	NA	NA	367	170000	0.2
Copper (thousand metric tons)	DRC	80000	1000000	8.0	2350	21900	10.7
	Eritrea	NA	NA	NA	21725	21000	0.1
	Mauritania	NA	NA	NA	28491	21000	0.1
	Tanzania	NA	NA	NA	12	21000	01
Graphite (natural) (metric tons)	Madagascar	26000000	330000000	7.9	110000	1300000	8.5
	Mozambique	25000000	330000000	7.6	170000	1300000	13.1
	Tanzania	18000000	330000000	5.5	8000	1300000	0.6
Lithium (metric tons)	Zimbabwe	310000	26000000	1.2	800	130000	0.6
	Mali	700000	26000000	2.7	NA	130000	NA
Manganese (thousand metric tons)	DRC	NA	NA	NA	15	20000	0.0
	Cote d Ivoire	NA	1700000	NA	360	20000	18
	Gabon	61000	1700000	3.6	4600	20000	23.0
	Ghana	13000	1700000	0.8	940	20000	4.7
	South Africa	640000	1700000	37.6	7200	20000	36.0
	Zambia	NA	NA	NA	30	20000	0.2
Nickel (metric tons)	Madagascar	NA	NA	NA	9900	2700000	0.4
	Zambia	NA	NA	NA	3251	2700000	0.1
PGMs (kilograms)	South Africa	63000000	70000000	90.0	220000	400000	61
	Zimbabwe	1200000	70000000	1.7	12000	210000	6.7
	Burundi	100	130000000	0.0	200	290000	0.1

Rare Earths (metric tons)	Madagascar	NA	130000000	NA	960	300000	0.3
	South Africa	790000	130000000	0.6	NA	300000	NA
	Tanzania	890000	130000000	0.7	NA	300000	NA
Tin (metric tons)	DRC	130000	4600000	2.8	20000	310000	6.5
	Nigeria	NA	NA	NA	1700	310000	0.5
	Rwanda	NA	NA	NA	2200	310000	0.7
Vanadium (metric tons)	South Africa	3500	26000	13.5	9100	100000	9.1
Zirconium (ores and concentrates)	Madagascar	NA	NA	NA	25.3	1200	21
	Mozambique	1800	68000	2.6	100	1400	7.1
	Senegal	2600	68000	3.8	70	1400	5.0
	Sierra Leone	NA	NA	NA	6.6	1200	0.6
	South Africa	5900	68000	8.7	320	1400	22.9

According to the International Energy Agency (IEA), over the next two decades, clean energy technologies could account for 40% of the total demand for copper and rare earth elements, between 60-70% of total nickel and cobalt demand, and almost 90% of lithium demand (IEA, 2021). Table 2 illustrates the minerals required for different clean energy technologies, where they are available in Africa, and the continent's share of global reserves (Table 2). 70% of global cobalt production comes from the DRC, 54% of manganese resources and 92% of platinum group metals (PGMs) are from South Africa (Pedro, 2021). As the world moves away from fossil fuels, the rising demand for critical minerals used to produce clean energy technologies holds the potential to lift some of Africa's poorest people out of poverty (UNCTAD, 2024). African countries have huge energy, housing and transport needs. In Africa, 120 million people do not have access to electricity, and 200 million people need modern, clean cooking solutions at home. The high deposits of critical minerals in Africa could make it easier to meet African citizens' needs by making it cheaper to achieve the sustainable development of clean energy sectors (IEA, 2024b).

Table 2. Africa's endowments in selected critical minerals. Source: UNCTAD, 2023; USGS, 2023; IRENA, 2023

Mineral	Clean energy technology	Share of global reserves in Africa	African countries with reserves
PGMs	Green hydrogen	92%	South Africa, Zimbabwe
Cobalt	EVs	56%	DRC, South Africa, Zambia, Madagascar
Manganese	EVs, wind	54%	Gabon, South Africa, Cote d'Ivoire, Ghana
Chromium	Geothermal, solar, wind	36%	South Africa
Bauxite	Wind, solar	24%	Guinea
Graphite	EVs	22%	Madagascar, Mozambique, Tanzania
Zirconium (ores and concentrates)	Green hydrogen	15%	South Africa, Senegal, Mozambique
Vanadium	Steel, batteries	13%	South Africa
Copper	EVs, wind, solar	6%	DRC, Zambia
Lithium	Batteries	4%	DRC, Zimbabwe, Mali
Nickel	EVs, wind	4%	Madagascar, South Africa
Tellurium	Solar	3%	South Africa
Rare earths	Wind	1%	Tanzania, South Africa, Madagascar, Burundi

The mining sector has also been one of the region's primary recipients of foreign direct investment. Revenues from copper and battery minerals production in Africa are already estimated at over USD 20 billion annually, and the current pipeline would imply a 65% increase in market value by 2030. In 23 African countries, minerals represent over 30% of total exports. Production of mineral resources is already a vital source of income for Africa, representing around 8% of government revenues in resource-rich African countries (Zero Carbon Analytics, 2024). According to McKinsey, Africa could generate between USD 200 million and USD 2 billion additional annual revenue by 2030 and create up to 3.8 million jobs by building a competitive, low-carbon manufacturing sector (McKinsey, 2021).

However, many African countries currently operate in the upstream segment, extracting minerals and exporting raw materials without substantial value addition (IRENA, 2023). There is a growing awareness among African policymakers about the importance of implementing strategies to improve and transform the value chains across sectors (Figure 2). To support the development of the domestic mineral value chain, several African countries, including the DRC, Nigeria, Zimbabwe, Namibia, and Ghana, have already adopted policies aimed at developing their mineral value chains, such as export restrictions on raw minerals (IEA, 2024) (Table 3). For example, Namibia has implemented a law banning the export of unprocessed mineral resources, and Ghana adopted the Green Minerals Policy, effectively banning the export of unprocessed mineral resources to retain value and bolster domestic supply chains. The DRC has used an intermittent export ban on cobalt and copper concentrates to force companies to process the minerals domestically, with a regular review of the export ban every six months (Zero Carbon Analytics, 2024).

Table 3. Most Restrictive Export Measure for Raw Minerals in Select African Countries. Source: OECD, 2024a

African Country	Most restrictive export measure
Angola	Export ban
Burundi	Export ban
Congo, Dem. Rep.	Export ban
Ghana	Export ban
Kenya	Export ban
Madagascar	Export ban
Nigeria	Export ban
Rwanda	Export ban
Gabon	Export tax
Guinea	Export tax
Namibia	Export tax
Senegal	Export tax
Sierra Leone	Export tax
South Africa	Export tax
Zambia	Export tax
Zimbabwe	Export tax

Since 2009, the severity of export restrictions on raw materials in Sub-Saharan Africa has increased. Table 3 shows that of the most restrictive measures, eight African countries imposed export bans, and eight countries charged export taxes. In 2009, the prior requirement of export licensing was the most restrictive export measure in Angola, Madagascar, and Zimbabwe. By 2020, Sierra Leone and Zimbabwe had imposed export taxes, while Angola and Madagascar imposed export bans. Senegal had no restrictions in 2009 but had implemented an export tax by 2021 (OECD, 2024b). In aggregate, while the number of countries imposing export restrictions on raw minerals and metals in Sub-Saharan Africa varied between 17 and 19 since 2009, the severity of the restrictions deepened.

3.2 Mine production of critical minerals in Africa (in metric tons)

Africa produces more than 60 metals and minerals. However, Africa's production represents only about 8% of global mineral production, and most of this production is exported in raw form (African Development Bank, 2012). Increased production of critical minerals from the continent would help diversify the global supply of critical minerals, reducing reliance on dominant producing countries and enhancing supply chain resilience.

The data source on the production of mineral materials in this section was World Mining Data, in which mineral materials are categorized into four groups: Iron and Ferro-Alloy Metals, Non-Ferrous Metals, Precious Metals, and Industrial Minerals. As Figure 3 illustrates, in 2022, the total mineral production in 43 African countries was 216 billion metric tons (mt) (Figure 3). The top 10 African countries by mine production are Guinea (103 million mt), South Africa (61.65 million mt), Morocco (12.2 million mt), Algeria (4.72 million mt), Gabon (4.52 million mt), Tunisia (3.98 million mt), Egypt (2.69 million mt), DRC (2.67 million mt), and Liberia (2.64 million mt).

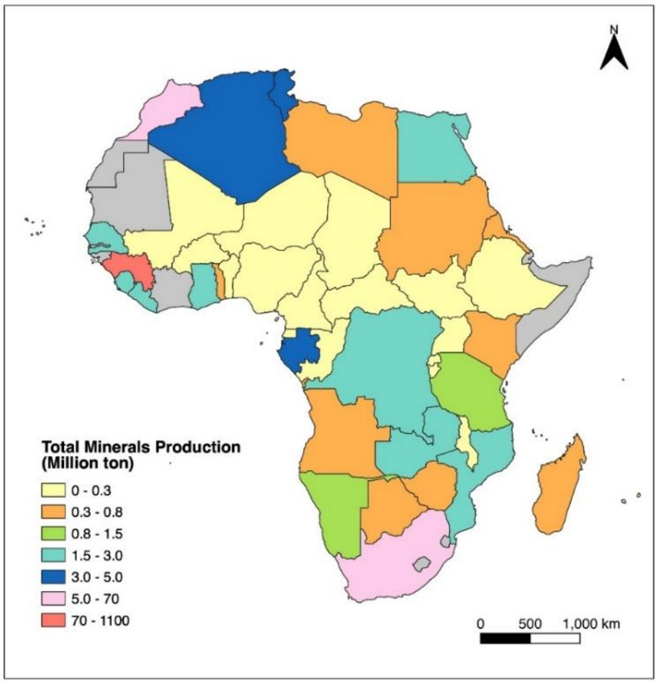


Figure 3. Mine production of mineral materials in Africa (2022). Source: World Mining Data, 2024

Guinea has various mineral resources, including alumina, bauxite, diamonds, gold, and significant undeveloped iron ore resources (USGS, 2024). Guinea is the world's third-ranked producer of bauxite, accounting for 19% of world output; the country also is a significant producer of diamonds. South Africa remained one of the world's leading mining and mineral-processing countries. South Africa's estimated share of world reserves of PGMs is 91%; manganese, 40%; chromite, 35%; vanadium, 16%; fluorspar, 13%; zirconium, 10%; and gold and ilmenite 5% each. In 2022, South Africa's iron ore production was 41.4 million mt, gold production reached 96.4 mt, platinum production amounted to 134 mt, and production of palladium was 78 metric tons. Morocco was the third largest minerals producer. In 2022, barite production in Morocco reached over 925,000 mt, accounting for the most significant mining production in the country. Other critical minerals outputs were sodium, feldspar, bentonite, and copper.

3.3 Mine production of critical minerals in Africa (by value)

Global revenues from the extraction of four critical minerals - copper, nickel, cobalt, and lithium - are estimated to total $16 trillion over the next 25 years. Africa stands to reap over 10 percent of these revenues, which could correspond to GDP growth of 12 percent or more by 2050 (IMF, 2024). Although the forecasts have high uncertainty, if appropriately distributed, revenues generated from the mining industry can help African economies strengthen their comparative advantage and achieve greater economic diversification. This could also create jobs in the processing sector, resulting in higher tax revenues and increased income from mineral exports.

Based on the annual average commodity prices from variable sources (e.g., USGS, U.S. Energy Information Administration, BGR-Rohstoffdatenbank), Figure 4 illustrates that the total value of mineral production in Africa was USD 270 billion in 2022 (Figure 4). The top 10 African countries for mine production measured by value are South Africa (USD 144 billion), DRC (USD 33 billion), Gabon (USD 14.4 billion), Zimbabwe (USD 12.3 billion), Ghana (USD 9.86 billion), Guinea (USD 8.9 billion), Zambia (USD 7.66 billion), Cote d'Ivoire (USD 4.68 billion), Mali (USD 4.1 billion), and Morocco (USD 3.89 billion). No data revealed what critical minerals mainly contributed to revenue generation in African countries. However, taking South Africa as an example, platinum group metals (PGMs) were the leading revenue-generating mineral commodity, collectively accounting for around USD 19.7 billion in 2023 (Statista, 2024). Gold ranked second, with approximately USD 4.9 billion in revenue.

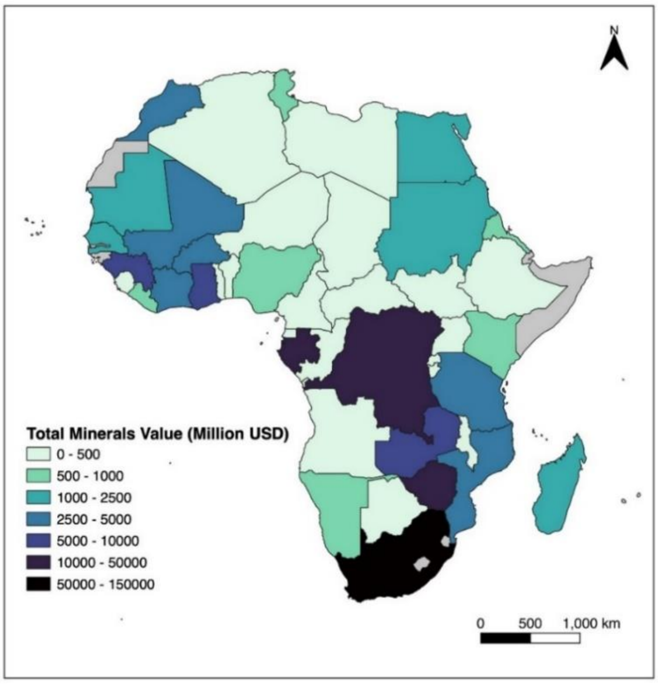


Figure 4. Mine production of critical minerals in Africa by value (2022). Source: World Mining Data, 2024

4. Outlook of critical minerals extraction for clean energy technologies

The global clean energy transitions will have far-reaching consequences for mineral demand over the next 20-30 years. Critical minerals, essential for a range of clean energy technologies, have risen to be high on the policy and business agendas in recent years. Demand projections are subject to considerable uncertainty, with different levels of climate ambition and various technology development pathways resulting in a wide range of demands for critical minerals. In this study, we assess the aggregate mineral demand from a wide range of clean energy technologies - mainly focusing on low-carbon power generation (renewables and nuclear), electricity networks, electric vehicles (EVs), battery storage and hydrogen (electrolyzers and fuel cells) (Table 4).

Table 4. Critical minerals demand for clean energy technology. Source: IEA, 2024a; IRENA, 2023

Minerals	Solar PV	Wind	EVs	Grid battery storage	Electricity networks	Hydrogen
Arsenic	○					
Boron		○				
Cadmium	○	○				
Copper	○	○	○	○	○	○
Cobalt			○	○		○
Dysprosium		○	○			
Gallium	○					
Germanium	○					
Battery-grade graphite			○	○		
Indium	○					
Iridium						○
Lead	○					
Lithium			○	○		
Molybdenum	○					
Manganese		○	○	○		
Nickel	○	○	○	○		○
Neodymium		○	○			
Praseodymium		○	○			
PGMs (other than iridium)						○
Selenium	○					
Silicon	○		○	○		
Silver	○					
Tellurium	○	○				
Tin	○					
Terbium			○			
Vanadium				○		
Yttrium						○

Zinc	O	O						
Zirconium								O

4.1 Demand outlook for critical minerals for clean energy technologies

Referring to IEA's scenario projection, a forward-looking analysis of critical mineral demand for major clean energy technology is based on the three main scenarios: (1) Stated Policies Scenario (SPS) maps out a trajectory that reflects current policy settings based on a detailed assessment of what policies are in place or are under development by governments around the world. (2) The Announced Pledges Scenario (APS) assumes that all long-term emissions and energy access targets, including net zero commitments, will be met on time and in whole, even when policies are not yet in place to deliver them. (3) Net Zero Emissions by 2050 (NZE) Scenario sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 (IEA, 2021, 2024b).

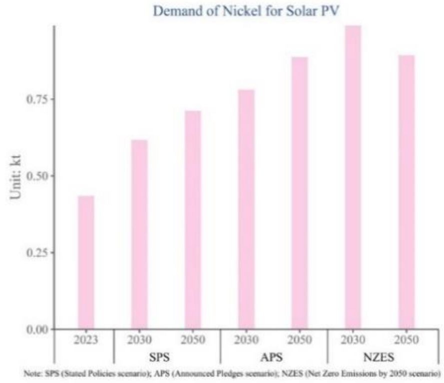
Critical mineral demand for clean energy technologies is projected to double between today and 2030 in the Stated Policies Scenario (SPS). It is even higher in the Announced Pledges Scenario (APS), and it is projected to almost triple by 2030 and quadruple by 2040 in the NZE Scenario. Until the mid-2010s, the energy sector represented a small part of the demand for most critical minerals. However, as energy transitions gathered pace, clean energy technologies became the fastest-growing segment for critical mineral demand.

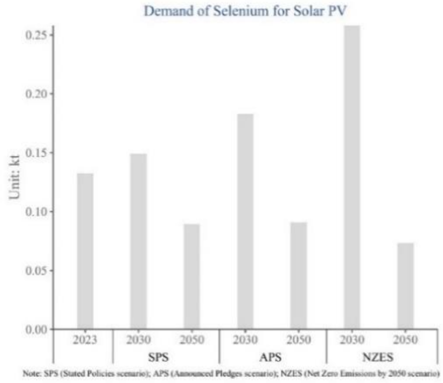
4.1.1 Solar PV

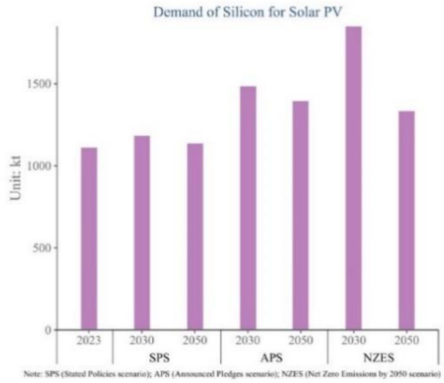
Solar PV plants mainly comprise modules, inverters, trackers, mounting structures, and general electrical components. Different module types require different critical minerals. For example, for utility-scale solar PV plants, crystalline silicon (c-Si) modules have become the dominant PV technology, followed by the "thin-film" alternatives: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si) (IEA, 2024a). Distributed solar PV systems require about 40% more copper than utility-scale plants. In the NZE scenario, capacity additions in 2050 are triple those of 2020, resulting in a near-tripling of copper demand for solar PV. The "thin film" technologies remain niche over the coming decades, and their use may be limited to applications where lower weight and greater flexibility are required, primarily in distributed and building applications.

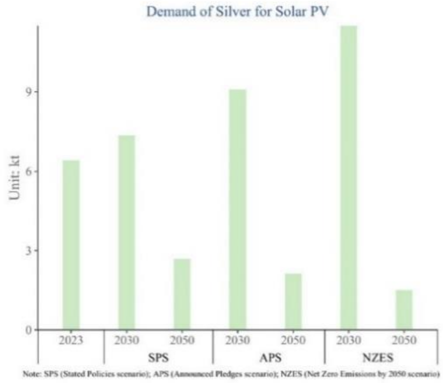
Crystalline polysilicon (c-Si) remains the dominant technology for PV modules, accounting for 95% of global solar PV additions in 2023. Although they are expected to continue to dominate over the coming decades, innovation in the manufacturing and design of c-Si modules over the past decade has contributed to significant reductions in materials intensity (IEA, 2023b). Material intensity reductions significantly dampen demand growth for silicon. As Figure 5 shows, despite higher annual capacity additions, the projection of demand for silicon by 2050 (1137 kt in the SPS and 1334 kt in the NZE scenario) is like its demand in 2023 (1110 kt) (Figure 5).

Continuous growth in the economic attractiveness of PVs, massive supply chain development, and increasing policy support, particularly from emerging economies like China and India, are expected to accelerate growth in the coming years. Maintaining a generation growth rate aligned with the Net Zero Scenario will require reaching annual capacity additions in 2030 close to three times higher than in 2022. Achieving this will require continuous policy ambition and effort from public and private stakeholders, especially in addressing policy, regulation, and financing challenges (IEA, 2024a).









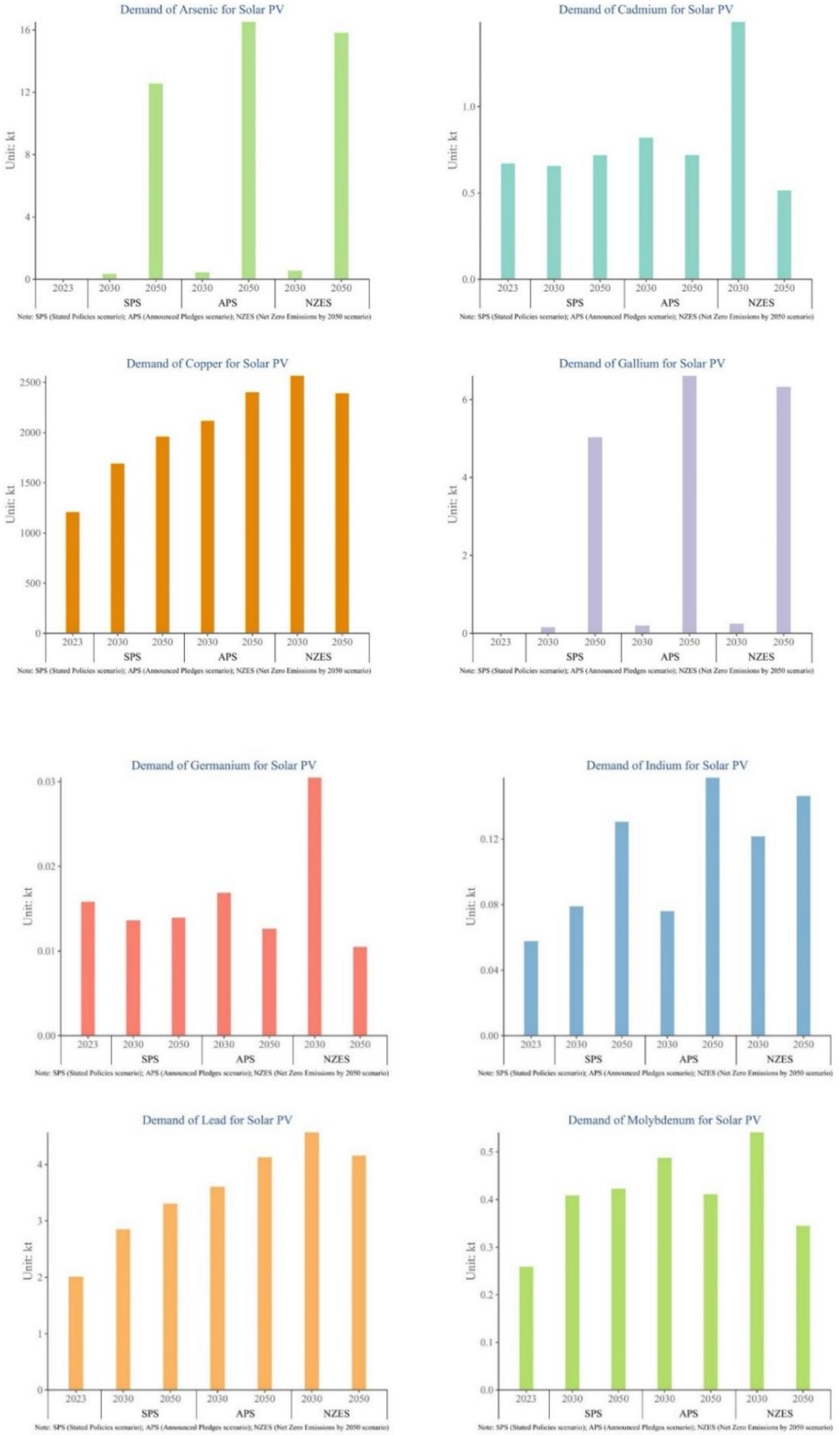
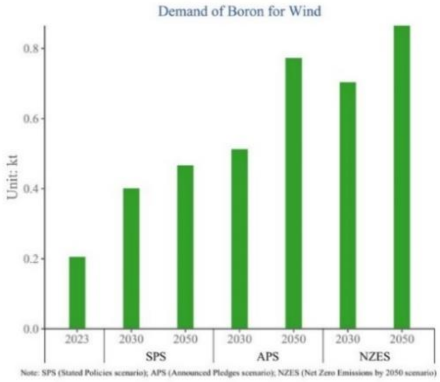


Figure 5. Critical minerals for Solar PV. Source: IEA, 2024a

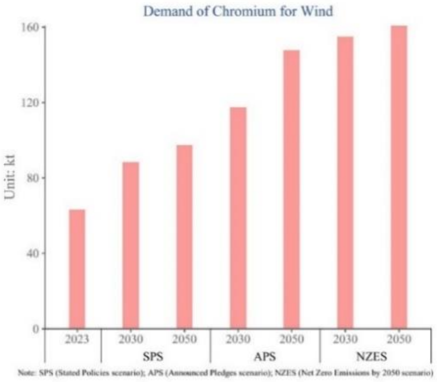
4.1.2 Wind

The global installed capacity of wind power has nearly quadrupled over the past decade (IEA, 2022). The share of offshore in total wind deployment is poised to grow considerably, as offshore wind offers higher capacity factors than onshore wind due to larger turbines that benefit from higher and more reliable wind speeds. As Figure 6 shows, the growing size of turbines drives a tremendous demand for critical minerals, with notably increased rare earth elements (i.e., praseodymium, neodymium, dysprosium, terbium) demand over the coming decades (Figure 6). Wind turbines consist of a tower, a nacelle, and rotors erected onto a foundation. They require concrete, steel, iron, polymers, aluminum, copper, zinc, and rare earth elements (IEA, 2023b).

Mineral intensities depend not only on the turbine size but also on the turbine type. For example, the offshore wind market is currently dominated by direct-drive permanent-magnet synchronous generator (DD-PMSG) turbines, which require neodymium, dysprosium, and relatively more significant amounts of rare earth elements. As projected in the SPS, demand for rare earth elements in wind-neodymium and praseodymium is set to more than triple by 2050. As a protective coating against corrosion, demand for zinc will increase from 704kt in 2023 to 1062kt in SPS and increase to 1745kt in NZE by 2050. Copper demand will reach 1451kt by 2050, propelled mainly by offshore wind requiring greater cabling.



Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)



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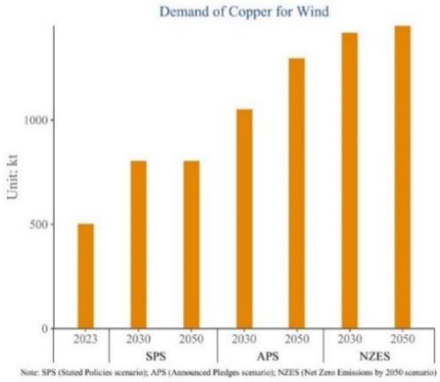

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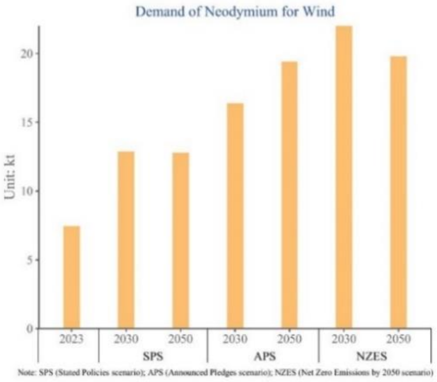

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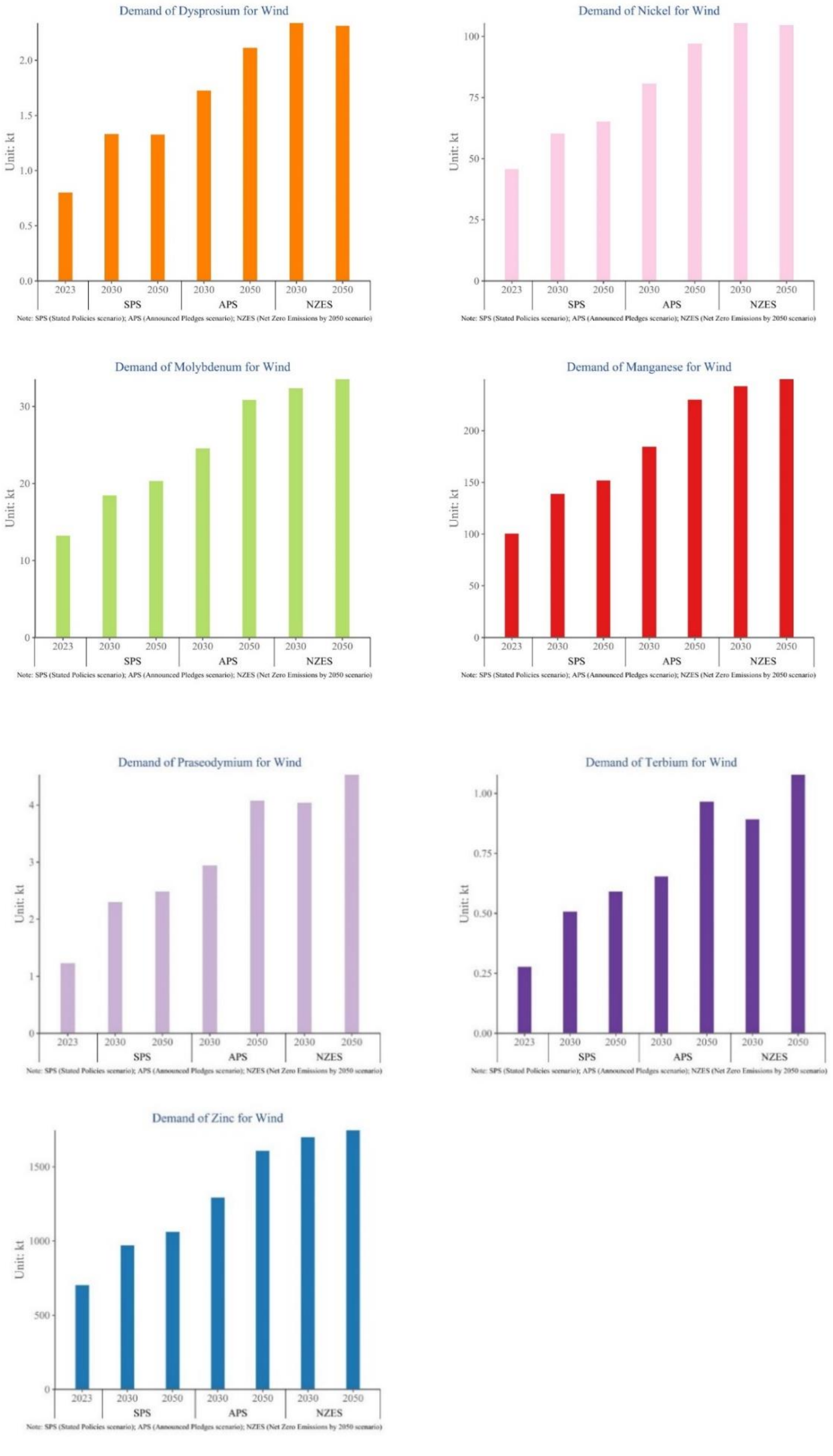


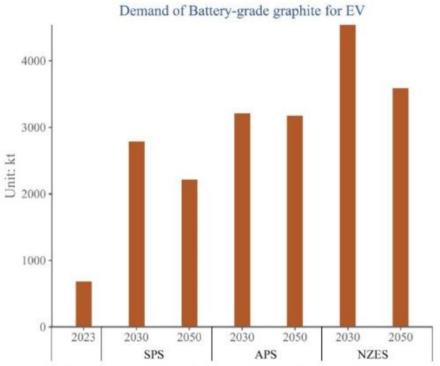
Figure 6. Critical minerals for Wind. Source: IEA, 2024a

4.1.3 Electric Vehicles

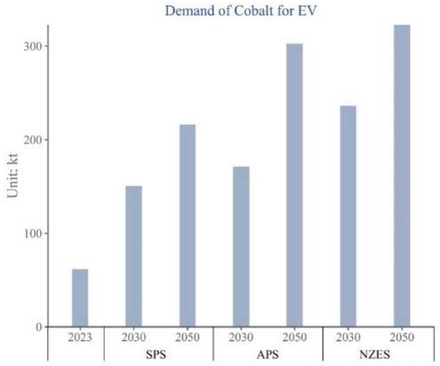
Most of the critical minerals in EVs are in two components: electric motors and batteries. Permanent-magnet motors have the highest efficiency and power density for electric motors, but their use of rare earth elements makes them expensive compared to other technologies. In addition to neodymium and other rare earth elements, permanent-magnet motors require copper, iron, and boron (Ballinger et al., 2019; Fishman et al., 2018). Other induction motors have the advantage of lower costs but only have moderate efficiencies due to electrical losses in copper windings. While induction motors do not require rare earth elements, they need a substantial amount of copper for the rotor cage and copper stator (IEA, 2023b).

The need for batteries varies considerably depending on the cathode and anode chemistries. For example, nickel manganese cobalt oxide (NMC) 111 batteries typically require almost eight times more cobalt than nickel cobalt aluminum oxide (NCA+) batteries but half as much nickel. Lithium iron phosphate (LFP) batteries do not require nickel, cobalt, or manganese but need about 50% more copper than NMC batteries (Blakemore et al., 2022). Alternative batteries demonstrate considerable sensitivity and uncertainty regarding the future mix of EV battery chemistries. While alternative batteries with low or no cobalt are gaining traction, the overall size of the EV market continues to expand, supporting demand growth in the medium to long term (IEA, 2024a; IRENA, 2023).

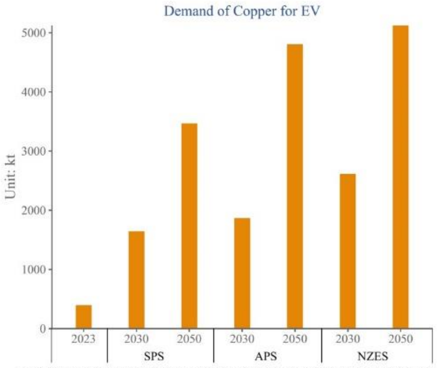
Due to all types of EVs requiring a substantial amount of copper, as Figure 7 shows, copper demand for EVs will experience the most significant growth, increasing more than twelvefold from 2% of demand in 2023 to 12% in 2050 (Figure 7). Nickel demand will grow to 1799 kt in 2050, while cobalt increases by only about 4 times as cathode chemistries shift away from NMC 111 towards lower-cobalt chemistries (NMC 622 and NMC 811). In addition to these three of the most in demand critical minerals, silicon registers the most significant growth, up over 61 times in NZE scenario, as graphite anodes doped with silicon grow from a 1% share in 2020 to 15% in 2040. Lithium demand grows by 11 times in SPS, and the demand grows by 17 times in the NZE scenario, while rare earth elements will grow from 6.57 kt in 2023 to 22.76 kt in 2030, and by another 8 times to 40.23 kt in 2050.


Demand of Battery-grade graphite for EV

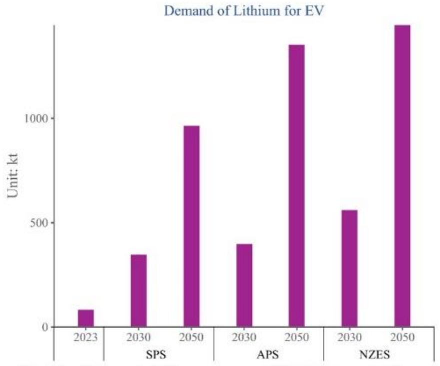
Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Cobalt for EV

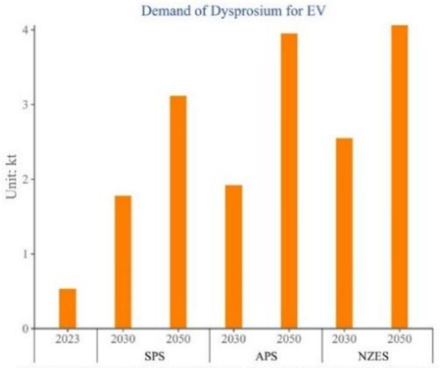
Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Copper for EV

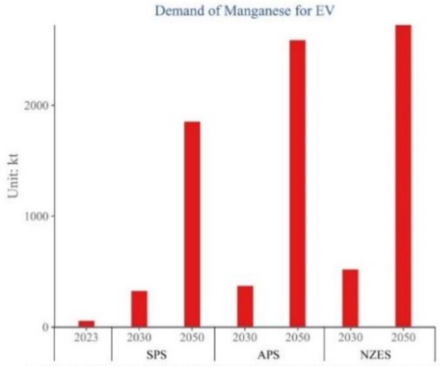
Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Lithium for EV

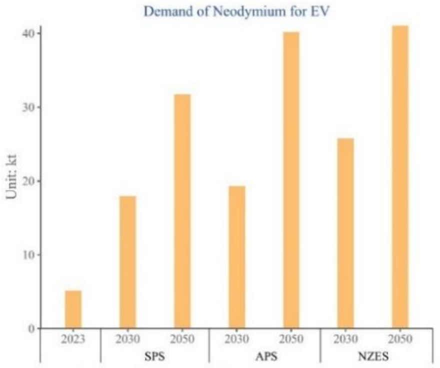
Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Dysprosium for EV

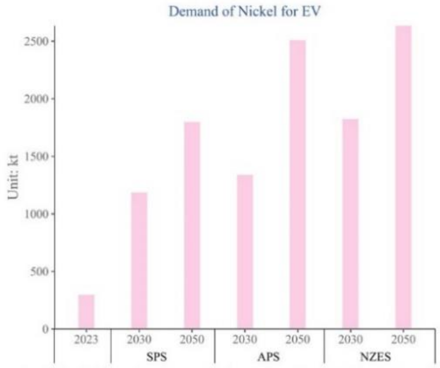
Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Manganese for EV

Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Neodymium for EV

Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)


Demand of Nickel for EV

Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)

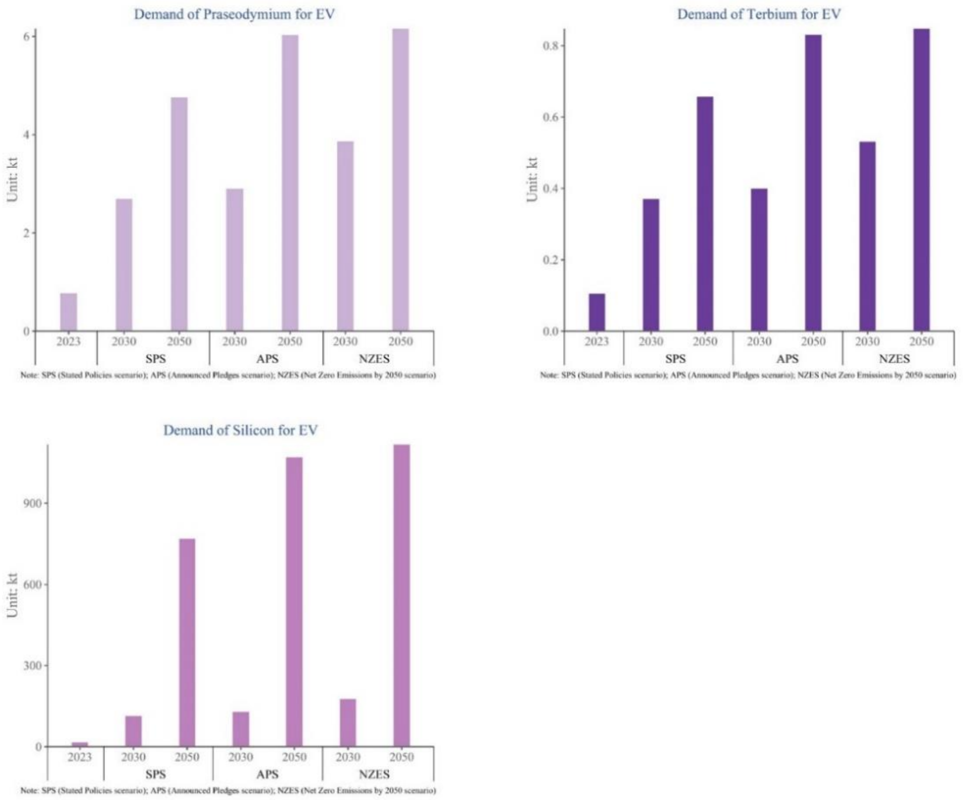


Figure 7. Critical minerals for Electric Vehicles. Source: IEA, 2024a

4.1.4 Battery storage

Battery storage in the power sector was the fastest growing energy technology in 2023, with deployment more than doubling year-on-year. Strong growth occurred for utility-scale battery projects, behind-the-meter batteries, mini-grids, and solar home systems for electricity access, adding 42 GW of battery storage capacity globally (IEA, 2024a). Built on the assumption that grid battery storage forms a significant proportion of the demand for critical minerals, figure 8 illustrates that demand for critical minerals will increase nearly 20 times, up to 2942 kt by 2050. The most significant growth is seen in the demand for copper, which grows more than 13 times from 22 kt in 2030 to 469 kt by 2050 in SPS, but the demand projection increases dramatically up to 898 kt by 2050 in NZE, a growth of 22 times compared to the demand by 2030. Demand for graphite will increase from 87 kt in 2023 to 1115 kt by 2050 in the NZE scenario, occupying the largest share of mineral consumption for battery storage growth (Figure 8).

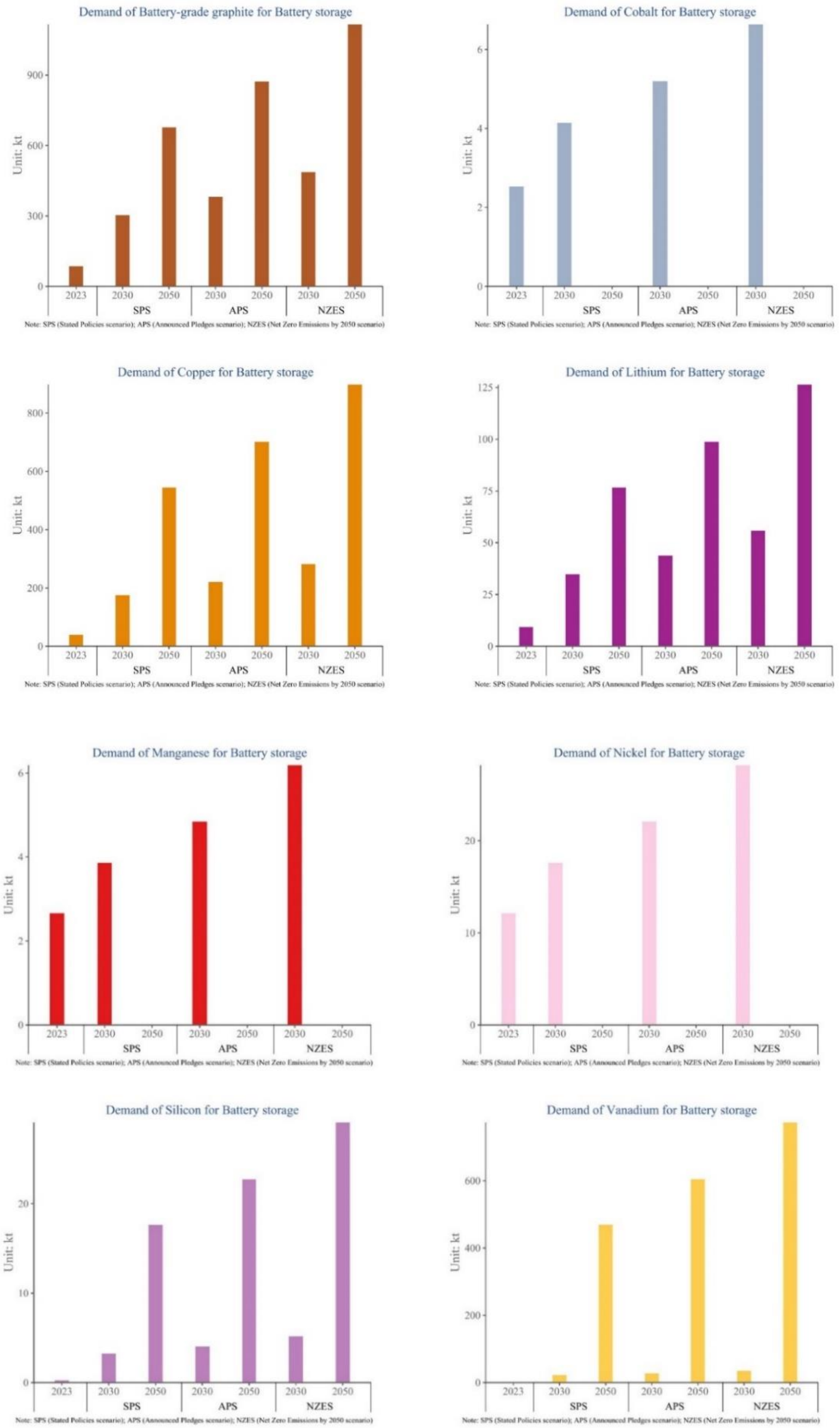
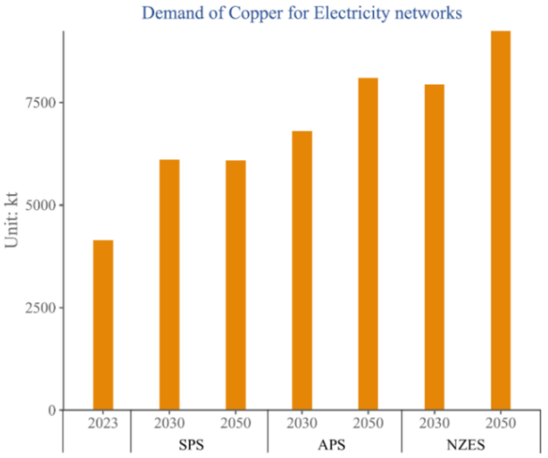


Figure 8. Critical minerals for Battery Storage. Source: IEA, 2024a

As utility-scale storage is expected to dominate the battery storage market, vanadium demand will increase 35 times by 2050. Thus, cost is the primary concern for technology selection; one of the alternative options is the commercialization of vanadium flow batteries, resulting in a growing demand for vanadium by 2050 compared to the current consumption. Compared with EVs, space constraints do not limit storage batteries, and the market is heading towards cheaper alternatives with lower energy density, such as LFP cathode chemistries or sodium-ion batteries, neither of which contains cobalt (IEA, 2024a).

4.1.5 Electricity networks

Electricity networks are the backbone of secure and reliable power systems. The projected demand for new transmission and distribution lines worldwide is 80% greater over the next decade in the SPS (Figure 9). The importance of electricity grids is even more significant in the case of faster energy transitions. Around 50% of the increase in transmission lines and 35% of the increase in distribution network lines is attributable to the rise in renewables (IEA, 2021).



Note: SPS (Stated Policies scenario); APS (Announced Pledges scenario); NZES (Net Zero Emissions by 2050 scenario)

Figure 9. Critical minerals for Electricity Networks. Source: IEA, 2024a

The massive expansion of electricity grids requires a large amount of minerals. For instance, copper is widely used for underground and subsea cables where weight is not a significant concern and superior technical properties (e.g., corrosion resistance, tensile strength) are required (IEA, 2023b). According to the projection of SPS, the annual copper demand for electricity grids will grow from 4143 kt in 2023 to 6084 kt by 2050, and the market is more than double that to almost 10000 kt in the NZE Scenario. As grids are modernized, expanded, and digitalized, the projected investment in electricity grids will reach USD 460 billion in 2030 in the SPS and USD 620 billion in the SDS.

However, shortfalls in grid revenues can put the adequacy of grid investment at risk. Prices for minerals may add to this pressure, given their considerable share of total investment costs. Using average prices over the past 10 years, copper costs are estimated to represent around 14% of total grid investment. The type of power line mainly drives the choice of raw material in electricity networks but is also influenced by cost and technical considerations. Higher prices of raw materials such as copper raise questions over how investment can reduce material intensity in the grids to lower material costs.

4.1.6 Hydrogen

Hydrogen applications play a fundamental role in sectors where emissions are hard to abate, but production needs to become cleaner, such as heavy industry and long-distance transport (IEA, 2022). Hydrogen demand remains concentrated in traditional applications in the refining and industrial sectors. Novel applications, such as transport, high-temperature heat in industry, power, and buildings, represent less than 0.1% of global demand. The growing market for electrolyzers could push up demand for nickel, platinum group metals, zirconium, and other minerals, depending on the specific technology deployed and the different electrolyzer types (IEA, 2021). Figure 10 illustrates that nickel will only increase by 5 times in the SPS, but the projection for growth is an increase by 80 times in the NZE scenario (Figure 10). Zirconium will increase by 2 times in the SPS but 77 times in the NZE scenario. Copper will increase by 90 times in NZE scenario, while in the SPS, the demand projection will only increase 6 times.

PEM electrolyzers have the advantages of smaller size, more flexible operation, and higher pressure output than alkaline, but the cost is much higher with shorter lifetimes. PEM catalysts use around 0.3 kg of platinum and 0.7 kg of iridium per MW (Kiemel et al., 2021). If PEM were to dominate the hydrogen market, it would increase energy-sector demand for platinum and iridium. Demand for iridium will increase by 10 times in the NZE, while PGMs (other than iridium) will increase by nearly 90 times.

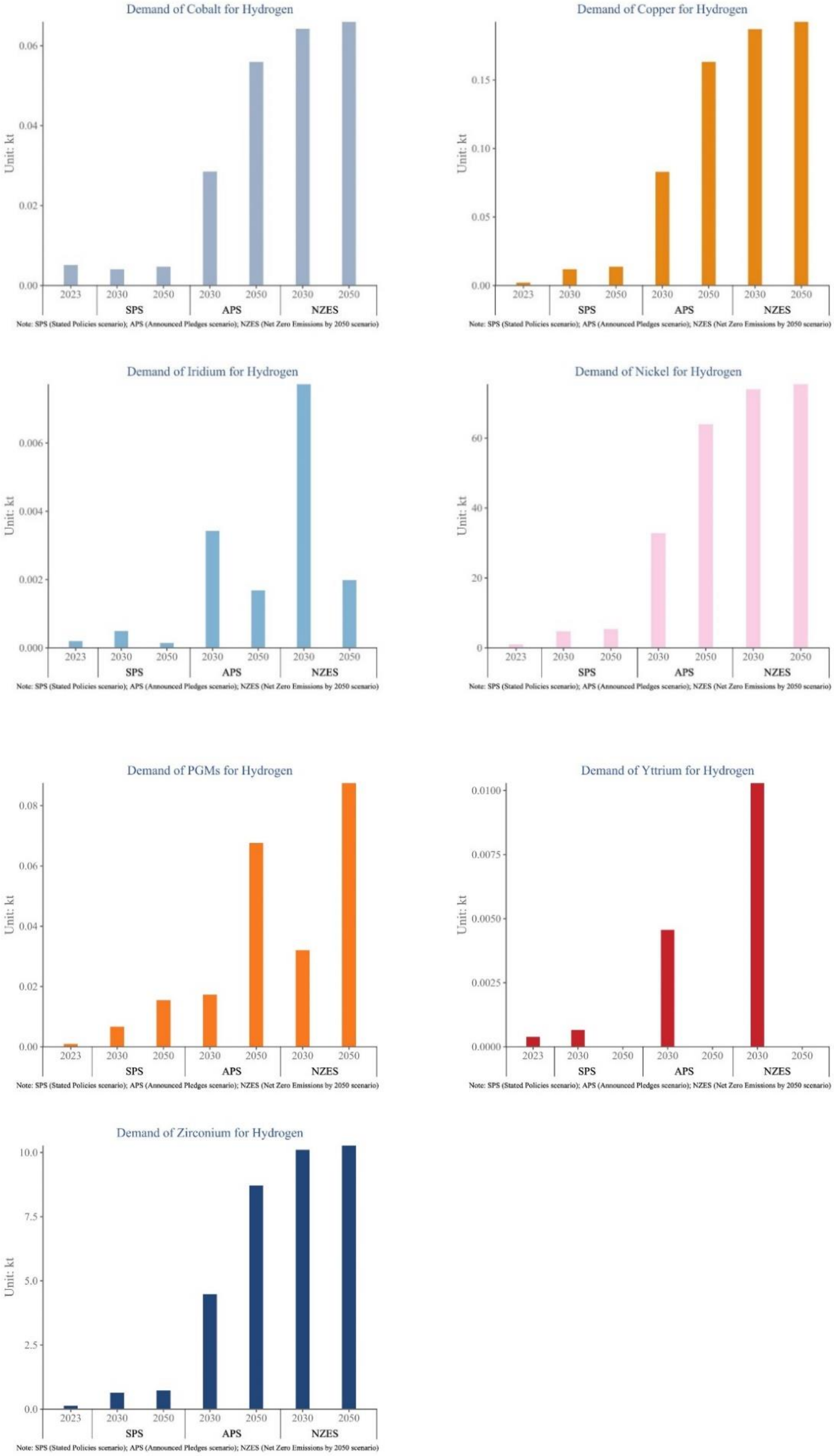


Figure 10. Critical minerals for Hydrogen. Source: IEA, 2024a

4.2 Outlook for the diversification of critical minerals supply

A forward-thinking approach to economic and energy security will center the diversification of mineral supply as a vital national interest. Disruptive innovation is adding to the uncertainty of future demand for critical minerals. Innovations in technology can influence demand by introducing substitutes, enhancing efficiency, optimizing designs, and incorporating new materials (Blakemore et al., 2022). The diversified chemical composition of electric vehicle (EV) batteries is a prime example (IEA, 2024c). Electric vehicle battery chemistry changes over the past years have significantly reshaped the demand for specific materials. Graphite-based anode chemistry holds a 70% market share due to its high performance. However, emerging anode chemistries, such as 100% silicon-based anodes, lithium anodes, and aluminum alloy anodes, can potentially reduce or eliminate the demand for graphite (IRENA, 2023).

NMC, NCA, and LFP are the most used cathode chemistries. New cathode materials are being deployed to reduce cobalt intensity for the dominant lithium-ion cathode, nickel-magnesium-cobalt (NMC), notably sodium-ion (Na-ion). This battery chemistry has the dual advantage of relying on lower-cost materials than Li-ion, leading to cheaper batteries and completely avoiding the need for critical minerals (Blakemore et al., 2022). Other emerging battery technologies, liquid metal batteries, zinc-ion batteries, and sodium-sulfur batteries, could disrupt the EV battery market by replacing critical materials such as lithium and cobalt with less expensive or more abundant options (IRENA, 2023).

Developing processes to recycle battery materials will also play an important role in diversifying critical mineral supply chains over the long term. Battery recycling is one of the most important secondary sources of energy transition critical minerals in the future, particularly lithium, nickel, and cobalt (IEA, 2024c). Presently, feedstock for mineral recycling mainly comes from end-of-life scrap and manufacturing scrap. However, the rapid growth in battery deployment means there will be a significant growth in batteries reaching the end of life and, therefore, battery manufacturing scrap generated from the production processes (Ballinger et al., 2019). The amount of spent EV batteries reaching the end of their first life is expected to surge after 2030, at a moment of continued rapid growth in mineral demand (IEA, 2023a). The security benefits of recycling can be far more significant for regions with broader deployment of clean energy technologies due to more significant economies of scale. Therefore, recycling should be regarded as a medium-to-long-term strategy to bolster the security of supply (IEA, 2024b).

The widespread application of advanced technologies has increased the demand for companion metals. More than 60% of companion or minor metals considered critical for the energy transition and digital technologies come as by-products (Nassar et al., 2015). Sustaining those uses may become a challenge because the production of companion metals is concentrated in a few countries and strongly influenced by the production of its host metals. The demand for these minor metals will continue growing exponentially because of the specific properties that make them indispensable for building clean energy solutions. One option for sustaining their supply is searching for substitutes to reduce the demand for companion metals. However, the best substitute for a companion metal is frequently another companion metal, often from the same host metal, because of similar physical and chemical properties (Willis et al., 2012). Furthermore, although substitution opportunities may exist in some cases, a transition to radically different technologies that use completely different metals is much more likely to change companion metal use than substitution (Peiró et al., 2013). Sustaining the supply of these companion minerals requires further research; this includes establishing a whole life-cycle approach from product design to product recycling of these companion metals (Grandell et al., 2016).

4.3 Overview of individual critical minerals in Africa

4.3.1 Arsenic

Arsenic is widespread in mining areas and is frequently associated with exploited metal sulfides. Arsenic can be obtained from copper, gold, and lead smelter flue dust and roasting arsenopyrite, the most abundant ore mineral of arsenic (USGS, 2024). High-purity arsenic is used to produce gallium-arsenide (Gaas), indium-arsenide, and indium-gallium-arsenide semiconductors that are widely used in biomedical, computer, electronics, light-emitting diodes (LEDs), and photovoltaic applications. Demand for high-purity arsenic will increase in military, space, telecommunications and solar cell applications. The use of Gaas components in cellular handsets and Gaas-based LEDs, automotive lighting, and other applications is expected to decrease in the short term, however, in the long term, consumption will increase because of the expansion of teleworking and virtual businesses (USGS, 2019).

Peru, China, and Morocco remained the leading global producers of arsenic trioxide, accounting for about 97% of estimated world production in 2023 (IEA, 2024b). In Morocco, arsenic was produced by Managem S.A.'s Bou-Azzer Mine as a byproduct of primary cobalt production. Figure 11 illustrates that Morocco accounts for around 10% of the global production of arsenic, but the production fluctuated slightly between 2018 and 2022 (Figure 11). In 2022, Morocco produced 5450 metric tons of arsenic, a decrease from 2021 (6883 metric tons). There is no available data on arsenic exports from Morocco, but according to USGS, China, and Morocco continued to supply about 91% of United States imports of arsenic trioxide in 2023, while China was the leading world producer of arsenic and supplied 98% of United States arsenic imports.

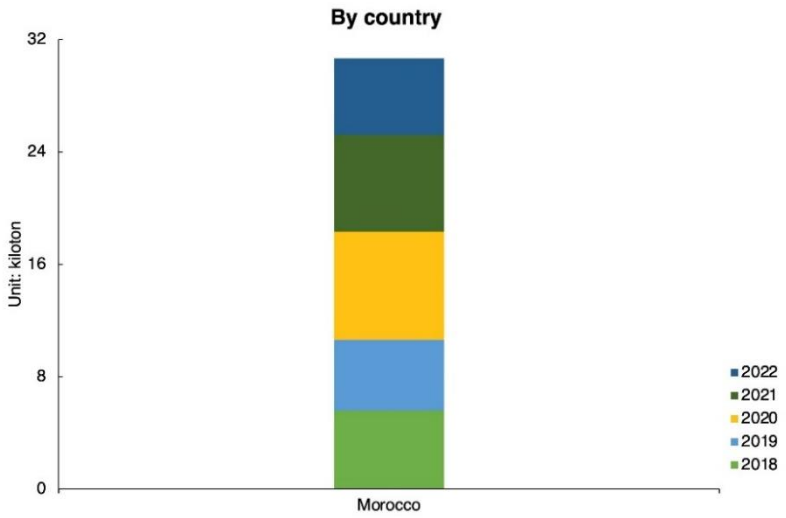


Figure 11. Mine production of arsenic in Africa. Source: World Mining Data

4.3.2 Copper

Copper is a critical mineral in all the most important clean energy technologies due to its unmatched combination of electronic conductivity, longevity, ductility, and corrosion resistance (IEA, 2024b). For example, copper is critical for lithium-ion batteries for EVs, being irreplaceable for the anode current collector used in the wiring in the battery packs and is a crucial component of EV motors (IEA, 2021). By 2030, electricity networks will become the most significant copper demand source; construction will become the leading source of refined copper demand in climate-driven scenarios by 2040.

The DRC copper belt is home to some of the highest-grade copper resources in the world; the Kamoa-Kakula mine produces a grade of copper that is ten times the global average (IEA, 2022, 2023b). Lower capital and production costs and emissions in the DRC significantly drive dramatic growth in copper supply. As Figure 12 shows, the production of copper in the DRC increased from 1.23 million mt in 2018 to 2.51 million mt in 2022, nearly double. With its remarkable growth in copper production, the DRC has doubled its share of global supply from 6% in 2015 to 12% in 2023, overtaking Peru as the second-largest supplier (Figure 12).

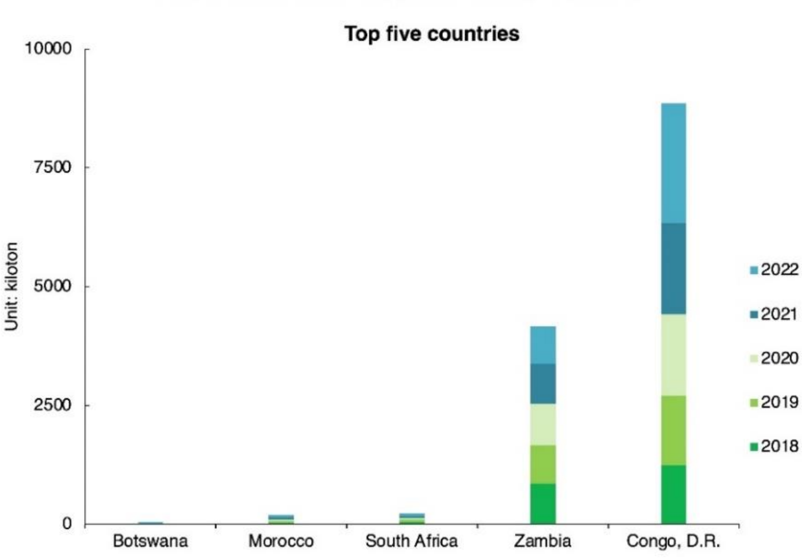


Figure 12. Mine production of copper in Africa. Source: World Mining Data

DRC is also the largest exporter of copper in Africa. Figure 13 shows that the total value of copper exported from Africa in 2022 was USD 29284 million (Figure 13). The DRC exported USD 19330 million of that, which is by far the largest share. Zambia is Africa's second-largest copper producer, and exports from Zambia were USD 8215 million in 2022. China is the largest importer of copper from the DRC. Switzerland imports more than half of its copper from Zambia (53%), while the EU imports 40% of its copper from Zambia, second after China (58%).

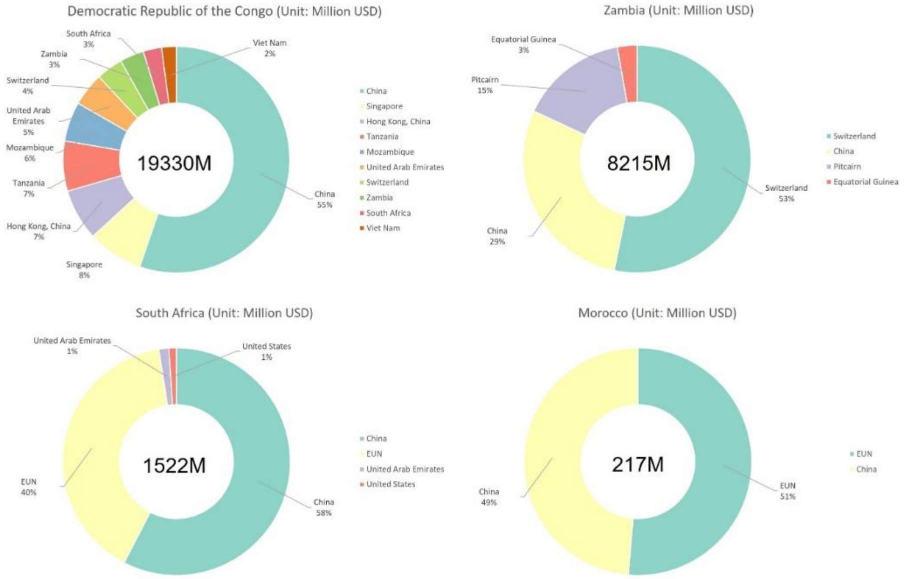


Figure 13. Exports of copper from Africa. Source: OECD, Trade in Raw Materials, 2024

IEA projects that the mined copper supply will reach around 25 Mt in 2026. The share in total mine production of the top three producers is projected to increase to 55% by 2040. Chile remains the largest producer going forward, and the DRC remains the second largest producer. China also continues to grow its share of global supply, from 8% in 2023 to 12% in 2040 (IEA, 2024a).

4.3.3 Cobalt

Cobalt is mainly extracted as a by-product of copper or nickel ore; the USGS shows that copper accounts for almost 70% of the supply of cobalt (USGS, 2023). Nickel plays a growing role as a primary mineral in cobalt production. With the rise of Indonesia's nickel production, 30% of the primary mineral refined into cobalt has been from nickel, and this share will increase by almost 40% by 2040 (IEA, 2024a) (Figure 14). Cobalt is used mainly in cathodes, rechargeable batteries, and superalloys for turbine engines in jet aircraft. Most current electric vehicle models use batteries, known as NMC; around 20% of cobalt is used for lithium-nickel-manganese-cobalt oxide chemistries (IEA, 2021).

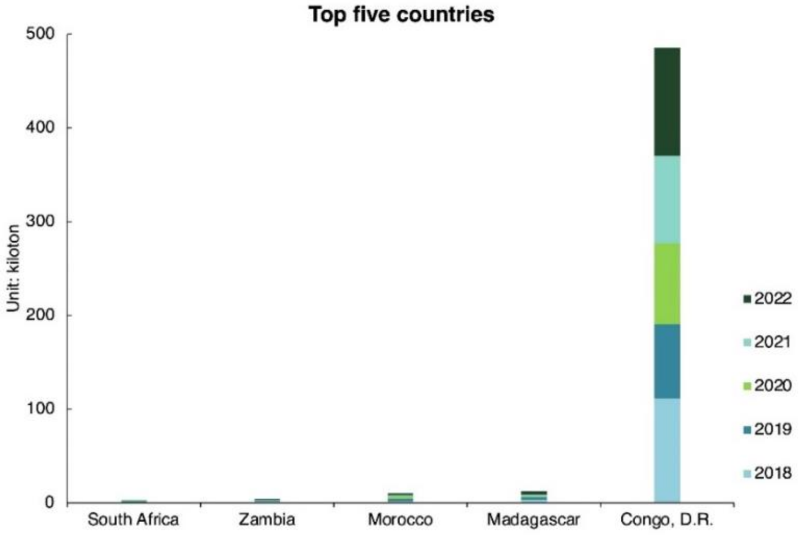


Figure 14. Mine production of cobalt in Africa. Source: World Mining Data

Nearly all cobalt in the DRC is sourced from copper deposits. The DRC produces about 63% of the world's cobalt, about 80% from industrial copper mines, and the remaining 20% from artisanal mining. Figure 14 shows that the DRC produced 115371 mt of cobalt in 2022, up slightly from 93000 metric tons in 2021. Cobalt production in the DRC is poised for significant growth soon as several new mines ramp up their output (IEA, 2023b). However, in the long term, existing mines in the DRC will likely reduce their supply or close due to diminishing ore grades and increasing production costs. As Figure 15 shows, in 2022, China was the leading importer of cobalt from the DRC, taking 38% of total exports (USD 3154 million) (Figure 15). South Africa was second largest importer of cobalt (USD 2075 million).

Madagascar, Morocco, and Zambia are primary producers of cobalt in Africa, but the total export of the three countries was less than 10% of that from the DRC.

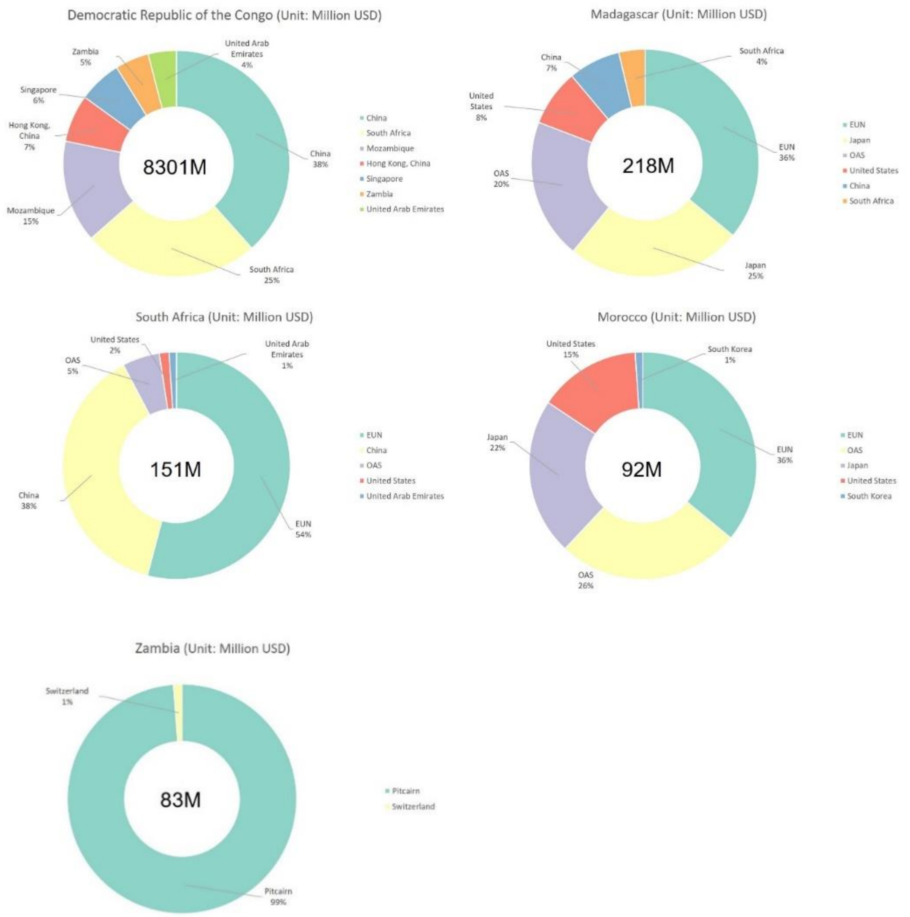


Figure 15. Exports of cobalt from Africa. Source: OECD, Trade in Raw Materials, 2024

The outlook indicates that although demand for EV batteries continues to rise, the recent trend towards low-cobalt or cobalt-free batteries slows the long-term growth of copper demand compared with other battery metals such as lithium and nickel. Besides batteries, cobalt is used the most in superalloys integral to the military and aerospace industries. As the industries consuming these superalloys are typically less price-sensitive, demand for cobalt in superalloys continues to remain robust (IEA, 2024a).

4.3.4 Graphite

As graphite maintains its dominant position in anodes, EVs and battery storage are rapidly emerging as the leading consumers of graphite, with projections indicating that it may account for over half of total demand by the late 2020s. Graphite production has increased dramatically in the last few years, catering to the growing battery market. China was the world's largest producer of graphite in 2023. However, China's share will decline to 70% in 2030 because new players are emerging producers in global graphite supply (IEA, 2024a). In Africa, Mozambique and Madagascar are the two biggest producers of graphite. In Mozambique, notably with the Ancuabe project (60 kt), and Madagascar, with the Molo project (150 kt), graphite production doubled between 2018 and 2022.

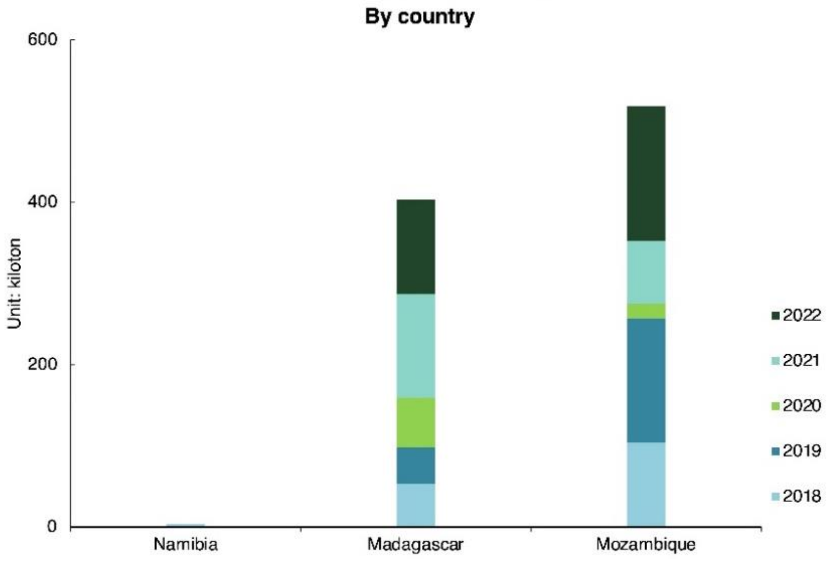


Figure 16. Mine production of graphite in Africa. Source: World Mining Data

Figure 16 illustrates that in Mozambique, Graphite production increased from 10400 mt in 2018 to 16600 mt in 2022, while Madagascar produced 116700 mt in 2022, more than twice its production in 2018 (53000 mt) (Figure 16). China is the largest importer of Graphite from Mozambique and Madagascar (Figure 17). In 2022, 59% of graphite was exported from Mozambique to China, while the EU and the US accounted for 19% and 13% respectively. From Madagascar, 48% of graphite was exported to China, and the EU and India imported 16% and 13%, respectively.

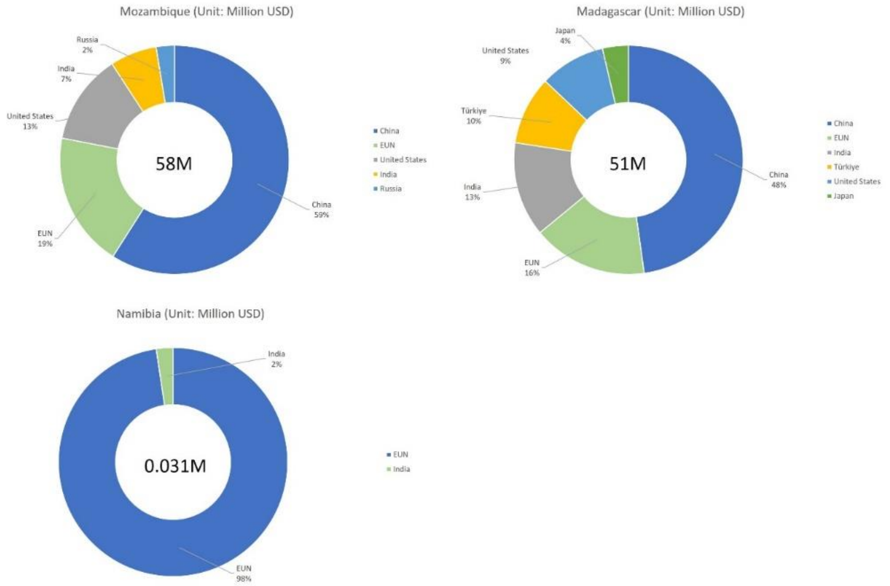


Figure 17. Exports of graphite from Africa. Source: OECD, Trade in Raw Materials, 2024

The EV industry emerges as a primary consumer of graphite. This sector will consume 5.4 mt by 2030, higher than current global production levels. According to IEA projections, the anticipated supply of natural and synthetic graphite will meet the demand from the EV industry in the short term. However, sustaining the long-term demand will require additional production. The supply of natural graphite may turn to a deficit over the next decade. Thus, a short natural graphite supply could result in a surging demand for synthetic graphite to offset the deficit (IEA, 2024a).

4.3.5 Lithium

Of all the minerals required for the clean energy transition, lithium is experiencing the most rapid growth in demand. Lithium production has more than doubled in the past three years, and the EV industry will contribute to about 90% of future lithium demand growth by 2050 (IEA, 2024a). Lithium mining is a recent phenomenon in Africa, where Zimbabwe's production has recently ramped up (Figure 18), with 9 kt of lithium exported every year as concentrates of various hard rock ores. As Figure 19 shows, lithium production in Zimbabwe was 3540 mt in 2022, double that of previous years (1670 mt) (Figure 19). New mining facilities are planned for Zimbabwe, and lithium mining in other African countries is also emerging, with projects in Ethiopia, Nigeria, Rwanda, Namibia, and Ghana.

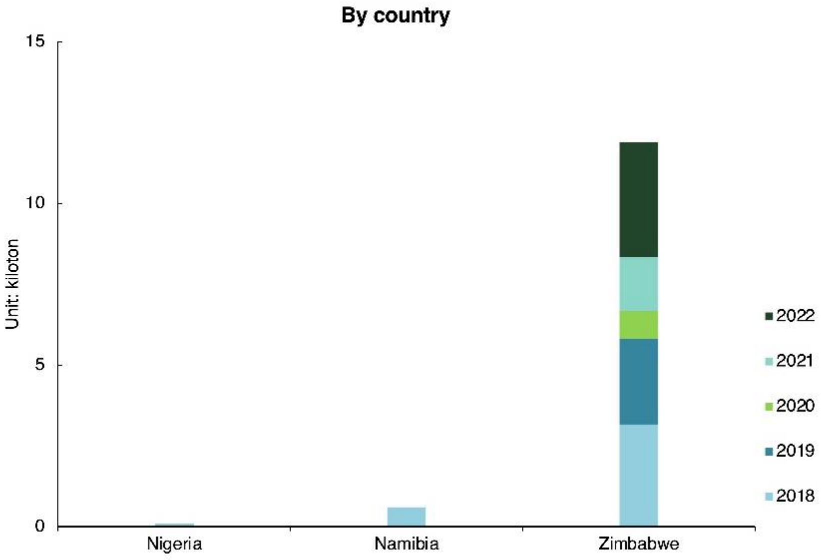


Figure 18. Mine production of lithium in Africa. Source: World Mining Data

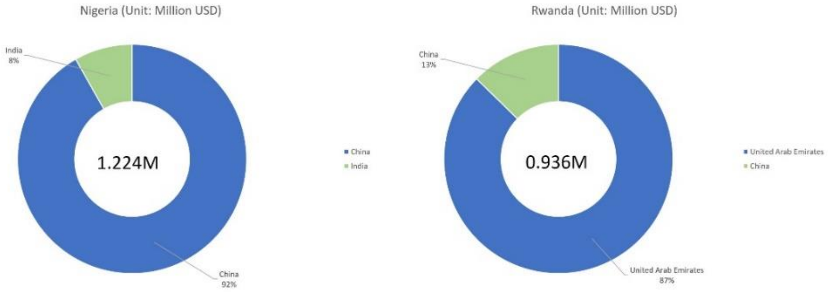


Figure 19. Exports of lithium from Africa. Source: OECD, Trade in Raw Materials, 2024

Africa’s total lithium production is predicted to rise to 70 kt by 2030 (IEA, 2024a). China is Nigeria's largest lithium importer, accounting for 92% of total exports. The UAE, an emerging player in Africa, imports most of its lithium from Rwanda, although the total value of imports is less than 1 million USD. Zimbabwe, which has Africa’s largest lithium deposits, in 2022, banned the export of unprocessed lithium with Statutory Instrument 213/2022, although some exceptions are allowed by the Ministry of Mines and Mining Development. The prohibition presents a window of opportunity for Zimbabwe to build domestic processing capacity and take advantage of the surging global price for lithium. However, forcing extractors to build processing facilities also risks increasing the cost of lithium projects in Zimbabwe and continues to fuel already-high global prices.

IEA estimated that the lithium supply will grow to 450 kt by 2030, doubling the current production and reaching five times the production level of 2020 (IEA, 2024a). Many mine projects are at their early stages of development, but price volatility may delay projects. Most importantly, the lithium market structure is sensitive to the respective market shares of different battery chemistries. Alternative technologies, such as sodium-ion and vanadium flow batteries, have begun to take a share from lithium-ion batteries in low-range vehicles and storage markets. However, they do not materially alter the prospects for lithium demand in climate-driven scenarios (IEA, 2021).

4.3.6 Manganese

Manganese is a critical component of one of the dominant EV cathode chemistries, lithium nickel manganese cobalt oxide (NMC). It is now being utilized in the new variant of the current leading chemistry LFP, known as lithium manganese iron phosphate (LMFP). The shift towards greater manganese contents in cathode chemistry is expected to drive a surge in demand for manganese (IEA, 2023b). According to IEA projection, by 2030, manganese demand from clean energy technologies will increase almost threefold in the SP Scenario, and nearly fivefold in the NZE Scenario. By 2050, manganese demand from clean energy technologies will be 11 times higher than today in the SPS, 16 times higher in the APS, and 17 times higher in the NZE Scenario (IEA, 2024a).

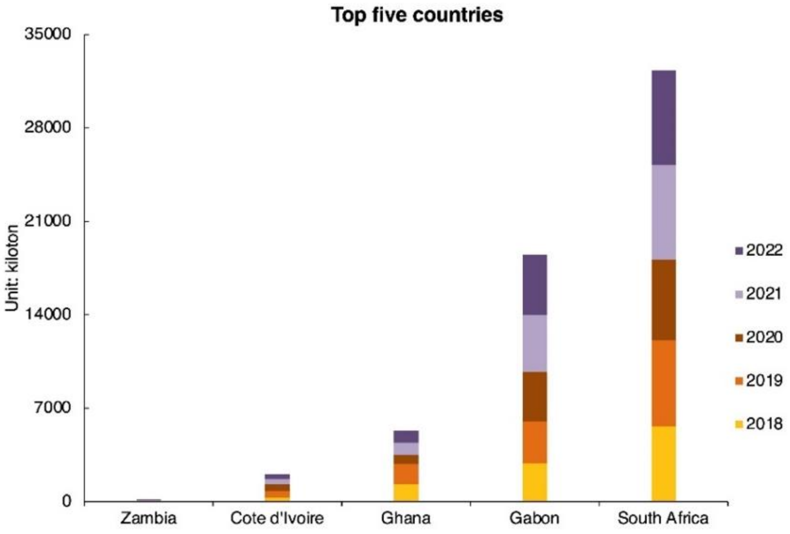


Figure 20. Mine production of copper in Africa. Source: World Mining Data

As Figure 20 shows, South Africa is the world's largest producer of manganese, with 35% of production, followed by Gabon with a quarter (Figure 20). In 2022, South Africa and Gabon produced 7.11 million mt and 4.52 million mt of manganese, respectively, while production in Ghana was relatively minor, with 0.9 million mt produced. China was the largest importer of manganese from Africa. Figure 21 shows that in 2022, China imported over 50% of manganese production from South Africa, at a value of USD 3052 million, while India was the second largest importer (13%). Cote d'Ivoire exported 78 % of manganese to China, and 13% was exported to India (Figure 21).

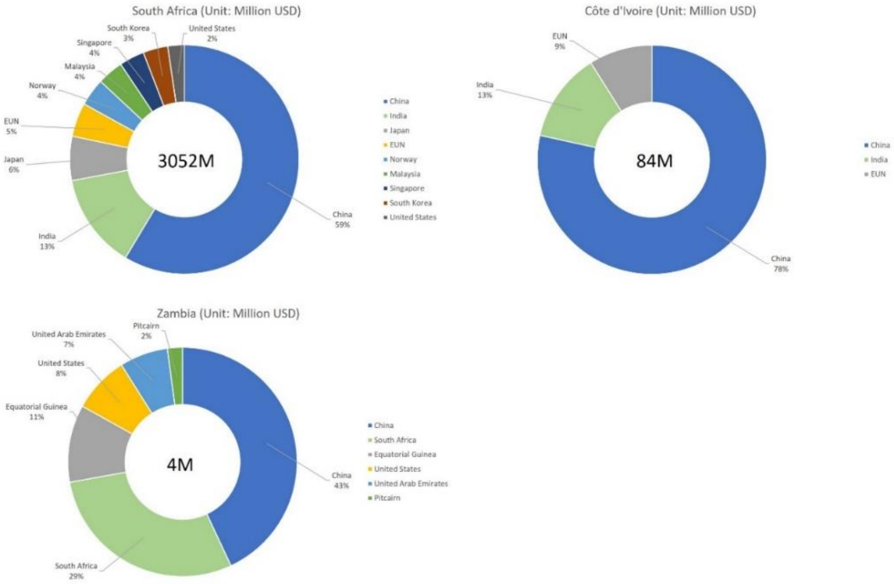


Figure 21. Exports of manganese from Africa. Source: OECD, Trade in Raw Materials, 2024

While manganese is abundant worldwide, only around 1% of the global supply is suitable for batteries (USGS, 2024). China dominates the supply of battery-grade manganese, producing 97% of the global supply. Today, China's dominance in the supply of high-purity manganese sulfates raises concern worldwide, making supply highly vulnerable to sudden changes in policy, geopolitics, or supply shocks (IEA, 2024a). Due to slight supply surpluses, battery-grade manganese prices are relatively low, proving challenging for new ventures in securing investments (IEA, 2023b). Some analysts forecast a deficit in the supply of battery-grade manganese as early as 2027, adding to concern for ensuring sufficient supply for EV batteries.

4.3.7 Nickel

The most significant applications of nickel in the clean energy sector are within EV batteries. Nickel is also used in low-emissions power generation, such as wind and geothermal (IEA, 2023b). South Africa is the leading producer of nickel on the continent. Figure 22 shows that in 2022, the total production of nickel in South Africa reached around 29500 mt, a slight decrease compared to the previous year when the output was 31900 mt (Figure 22). In the same year, nickel production in Madagascar was higher than in South Africa, and the volume was 35737 mt. Although Zimbabwe's production is much lower than South Africa and Madagascar, the nickel (sulphidic nickel) deposits account for about 3.1% of the global nickel resources, equivalent to about 3.658 million tonnes (IEA, 2023a).

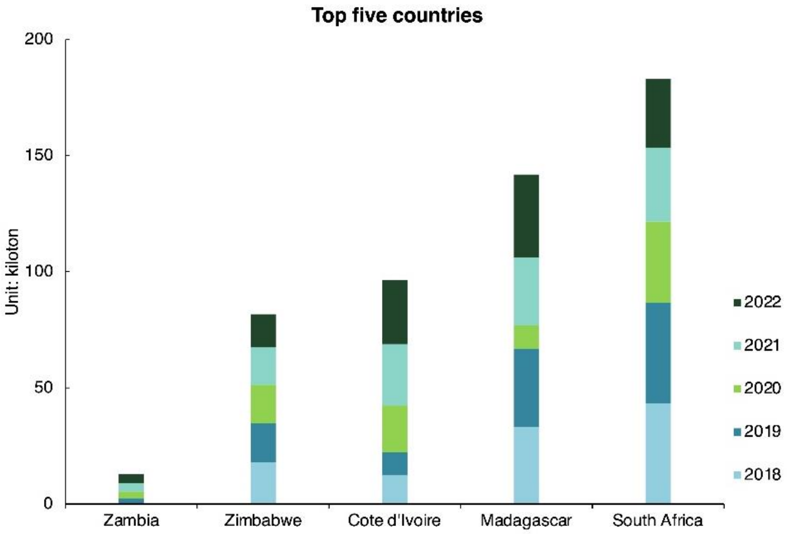


Figure 22. Mine production of nickel in Africa. Source: World Mining Data

As Figure 23 shows, Zimbabwe exported nickel with a total value of USD 2127 million in 2022, making it the 14th largest exporter in the world (Figure 23). South Africa was the largest importer from Zimbabwe, accounting for 98% of the total value. Japan, China, and South Korea were the top three importers of nickel from Madagascar with 41%, 28% and 17% respectively. EU, China, and the US were the significant nickel importers from South Africa and Cote d'Ivoire, while Switzerland imported all the nickel from Zambia.

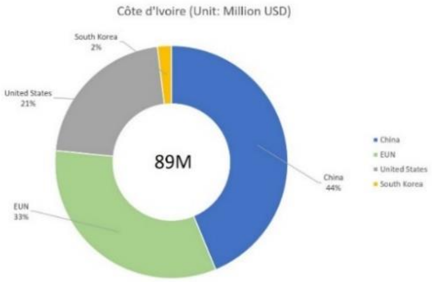


Figure 23. Exports of nickel from Africa. Source: OECD, Trade in Raw Materials, 2024

Clean energy technologies continue to drive overall growth in nickel demand. The primary driver of nickel demand growth in all projected scenarios is EV batteries, which will increase approximately ninefold by 2050 (IEA, 2024a). The market demand for nickel will be well supplied in the near term, but additional projects will be needed to meet medium- and long-term demand. IEA has identified approximately 25 operating or potential mines that could be at risk if the current low nickel price persists, primarily located in the region with the higher costs. Closing these nickel mines would lead to a shortfall and further reduce the diversity of the supply in an already geographically concentrated market (IEA, 2021).

4.3.8 PGMs

The platinum group metals (PGMs) are excellent electrical conductors and are used extensively in electronics. The largest consumer of PGMs is the automotive industry for catalytic converters. Platinum, iridium, ruthenium and palladium are essential industrial resources used along the hydrogen supply chain and will see increasing use in other energy transition applications (USGS, 2024). Electrolysers are electrochemical devices that convert water into hydrogen and oxygen, and their market share is anticipated to experience significant growth. According to IEA, in a future scenario where PEM technologies might represent around 50% of the global electrolysis capacity, the primary raw materials used for their deployment, i.e. iridium, could face constraints in the global market.

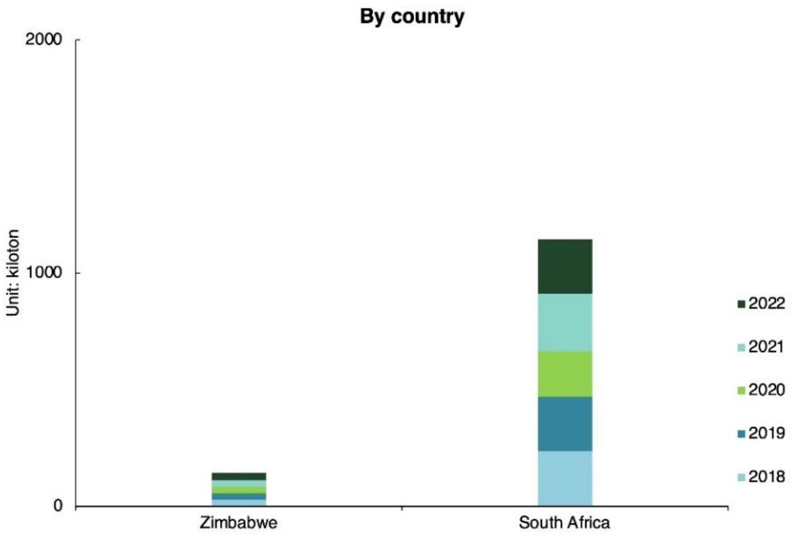


Figure 24. Mine production of PGMs in Africa. Source: World Mining Data

Figures 24 and 25 show that South Africa is the world's largest producer of PGMs, with more than 90 percent of global reserves (Figure 24, Figure 25). In 2022, South Africa produced 134750 kilograms of platinum and 78155 kilograms of palladium. Zimbabwe is also a significant producer of platinum and palladium, with 16460 and 13935 kilograms of both metals produced respectively. In 2022, South Africa exported USD 16.7 billion of PGMs. Japan was the largest importer, accounting for 36% of South Africa's PGMs exports, while US imports from South Africa accounted for 28 % of its exports. For over 80% of Zimbabwe's PGMs were exported to South Africa, which was valued at USD 150 million, with the remainder exported to the US.

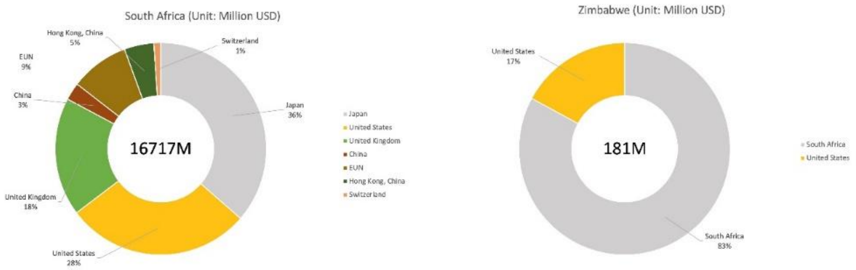


Figure 25. Exports of PGMs from Africa. Source: OECD, Trade in Raw Materials, 2024

Demand for iridium and ruthenium will likely increase thanks to the demand for membrane electrodes. However, divergent market outlooks complicate strategic decision-making for these elements of the PGMs basket. For example, increases in the demand for platinum remain subject to the future sales of hydrogen fuel cell vehicles. However, given the relatively small contribution of iridium and ruthenium to the PGMs family, prices for PGMs seem unlikely to increase meaningfully in the short term. Since 2023, several South African PGMs miners have announced cost-cutting measures to mitigate the impact of low prices. If the current low price continues, further closures might occur, jeopardizing long-term primary supply for all PGMs (IEA, 2024a).

4.3.9 Vanadium

The vanadium market is primarily driven by steel consumption, accounting for about 90% of Vanadium use. Other important applications include titanium alloys, catalysts and ceramics (IEA, 2022). In recent years, the application attracting the most interest is Vanadium Redox Flow Batteries (VRFBs), a new energy storage device. The commercialization of VRFBs will likely result in 2.5 times more demand for vanadium in 2030 and 50% more demand in 2040 (IEA, 2024b). With an expected growth rate of more than 20% per annum, VRFBs will capture almost a third of the energy storage market by 2050, with significant applications in wind and solar farms (Boni et al., 2023).

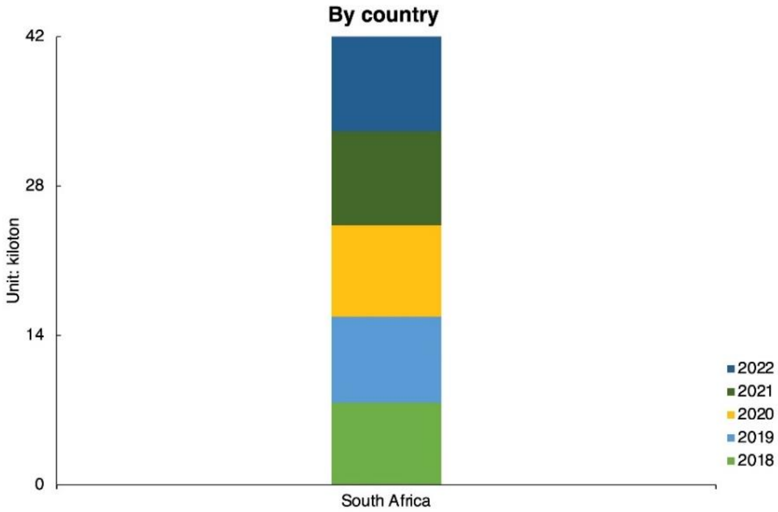


Figure 26. Production of Vanadium in Africa. Source: World Mining Data

South Africa holds the biggest vanadium ore resources globally. The country's vanadium production was highest in 2015 at 17460 metric tons. In 2022, the total volume of vanadium production in South Africa reached around 8870 mt and in 2023, it was 91000 mt (Figure 26). As Figure 27 shows, in 2022, exports of vanadium from South Africa were valued at USD 98 million; the US imported the largest share of vanadium at 29%, while Canada imported 24% of the total production (Figure 27). The EU and Japan were the major importers of vanadium, and Mozambique imported 9% as an intra-trade partner in Africa.

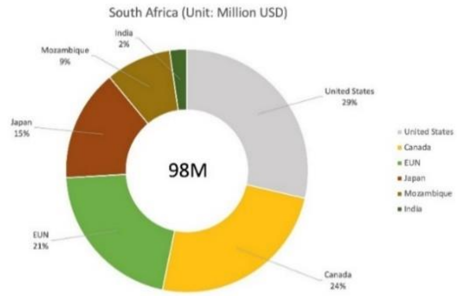


Figure 27. Exports of vanadium from Africa. Source: OECD, Trade in Raw Materials, 2024

The future VRFB market is poised for extraordinary growth, with a 22-fold increase expected by 2030. South Africa holds the highest-grade primary vanadium resources globally, leading to growth in demand in the energy sector, and could benefit strongly from exploiting its resources. Many other African countries, such as Namibia, Botswana, and Zambia, and some in Northern Africa, where this mineral could be profitably extracted as a by-product from other economic ores, will probably be at the forefront of vanadium production in the future (IEA, 2021).

4.3.10 Zirconium

Zirconium is used in various clean energy technologies, including solid oxide fuel cells that provide reliable and affordable portable power.Zirconia (zirconium dioxide) ceramics provide coating protection for jet turbines, and stabilized zirconia is used in hydrogen fuel cells to produce clean power. It can also operate in reverse as a hydrogen generator. The growing electrolyzer markets could push up demand for zirconium. For example, in 2023, the global installed capacity of electrolyzers for hydrogen production reached 1.3 GW, underpinned by a surge in annual additions to 600 MW, while 1 MW of alkaline electrolyzer could require around 100 kg of zirconium today.

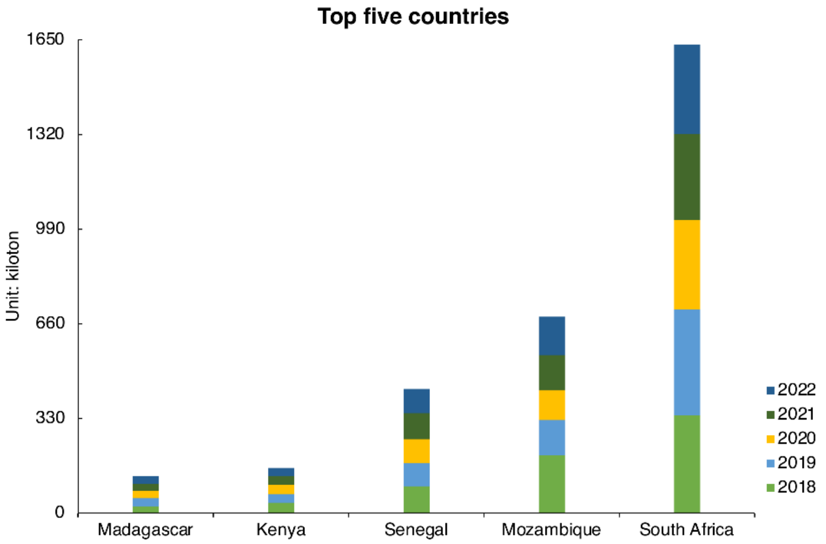


Figure 28. Mine production of zirconium in Africa. Source: World Mining Data

Global mine production of zirconium increased to about 1.6 million tons in 2023 (USGS, 2024). South Africa is the largest producer of zirconium on the continent (Figure 28). As of 2022, zirconium production in South Africa reached 310000 mt, with an export value of USD 640 million. Other main producing countries are Mozambique (134082 mt), Senegal (84062 mt), and Kenya (29715 mt). Figure 29 shows the countries that China imports zirconium from across Africa, which are South Africa (51%), Senegal (22%), Mozambique (48%), Kenya (66%), and Madagascar (91%) (Figure 29).

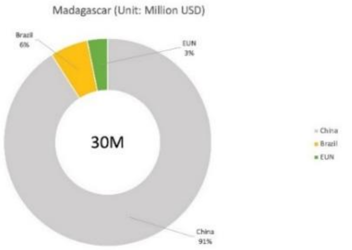


Figure 29. Exports of zirconium from Africa. Source: OECD, Trade in Raw Materials, 2024

The Zirconium market is projected to reach USD 3409 billion by 2030 after growing at a CAGR (Compound Annual Growth Rate) of 8.1% from 2024 to 2030 (Industry ARC, 2024). China's robust industrial base and focus on technological advancements contribute to its dominant position as a zirconium importer. Other regions, including North America, Europe, and Africa also play significant roles. However, the demand uncertainty and lack of regulatory clarity, coupled with recent challenges such as inflation and slow implementation of support mechanisms, hinder faster electrolyzer adoption and demand for zirconium in other regions (IEA, 2024a).

4.3.11 Zinc

Zinc is the fourth most-used metal in the world, behind iron, aluminum, and copper; it has increasingly become an essential material in low-carbon economies (IEA, 2024a). For example, zinc-ion batteries are considered safer than lithium-ion batteries as they use water-based chemistry, avoiding the fire problem with lithium-ion batteries in electric vehicle (EV) battery packs (IEA, 2023b). Figure 30 shows that over 500000 mt of total zinc was produced in Africa in 2022 (Figure 30). South Africa was the leading zinc producer in Africa, with a volume of zinc production reaching 224400 mt. Burkina Faso and Eritrea were other primary producers, with amounts of 120529 mt and 22880 mt respectively.

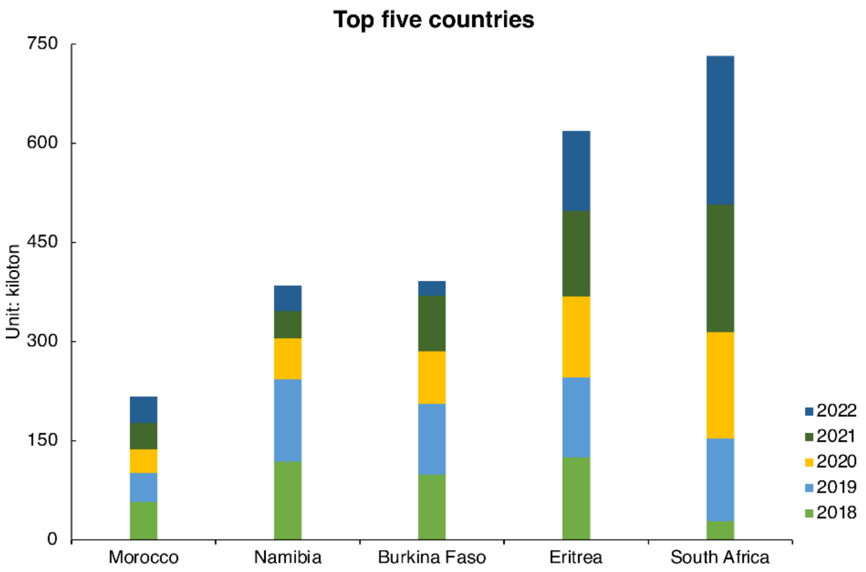


Figure 30. Mine Production of Zinc in Africa. Source: World Mining Data

China is the largest importer of zinc from Africa. As Figure 31 shows, in 2022, China imported 100% of zinc of production from South Africa at USD 531 million (Figure 31). In the same year, China imported 40% of zinc produced by Namibia (USD 80 million) and 51% from Morocco (USD 65 million). The EU and Canada are the other primary destinations for zinc from Africa. Cote d'Ivoire imports 100% of zinc from Burkina Faso (USD 55 million), making it the only intra-African trading partner on the continent.

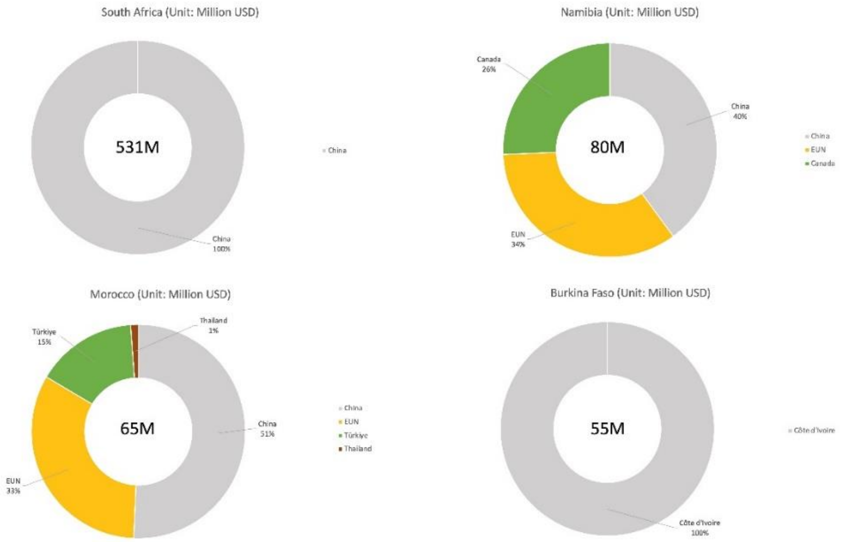


Figure 31. Exports of Zinc from Africa. Source: OECD, Trade in Raw Materials, 2024

The global demand for zinc in clean energy technologies will increase in the next decade, from 109300 mt in 2020 to 364000 mt in 2030. The International Zinc Association (IZA) estimates that the market share of zinc-ion batteries will increase from 1% in 2021 to 20% by 2030. Solar energy is expected to account for the largest share of zinc consumption, with a forecast volume of 162000 mt in 2030 (Statista, 2024).

5. Strategies of global players in the extraction of Africa's critical minerals

The distribution of critical minerals is highly concentrated geographically, posing challenges related to resource security and geopolitical dynamics (Way, 2024). Many countries recognize the strategic importance of mineral supply chains and are compiling or updating national critical material strategies. This section provides a comprehensive review of the strategies advanced economies have adopted for extracting Africa's critical minerals. African countries must adopt policy measures and strategies of their own to ensure they retain sovereignty and make the most of their mining sectors.

5.1 China

The Chinese National Plan for Mineral Resources (2016-2020) mapped the development direction of China's exploration and utilization of mineral resources and created a strategic mineral catalog consisting of three types of minerals, energy minerals, ferrous minerals, and non-ferrous minerals (the State Council of the People's Republic of China, 2016). In 2018, the 'Definition of China's Strategic and Critical Mineral Catalog for the New Era' was re-launched, categorizing 21 resources as strategic minerals. China has abundant reserves of some, while some others need to be imported by China. There is no unified understanding of the connotations of critical mineral resources in China, but the Fourteenth Five-Year Plan for National Economic and Social Development addressed the problem of securing the supply of strategic mineral resources, which has been elevated to a high level of national importance.

China is the world's largest importer of mineral products, becoming the world's largest metal refining hub (Way, 2024). Over the past 20 years, China has secured advantageous supply chains for copper, cobalt, magnesium, graphite and other critical minerals in Africa. Since the Forum on China - Africa Cooperation (FOCAC) was settled in 2000, China has established strategic partnerships with at least forty-four African countries, and Chinese foreign direct investment in African minerals increased from USD $75 million in 2003 to USD $4.2 billion in 2020 (Centre for Strategic and International Studies, 2024). Taking the DRC as an example, China relies almost entirely on the DRC for mined cobalt. The DRC produces roughly 70 percent of the world's cobalt, in 2020, Chinese firms had stakes in 15 of the 19 cobalt-producing mines after a US firm sold one of the DRC's largest copper-cobalt mines to a Chinese enterprise in 2020 (Reuters, 2020).

Although China has invested heavily in the extractive sector in Africa, currently, China controls only an estimated 8 percent of Africa's mining sector, still less than half its Western competitors. This statistic underlines the often inflated perception Western media fosters about China's mining operations in Africa. What really concerns the Western economies is China's monopoly over mining in Africa's copper belt (the DRC and Zambia), and its substantive recent investments into lithium production in Zimbabwe, which holds Africa's largest reserves of lithium (Wilson Centre, 2024). These investments allow China to dictate the global supply chain for semiconductor, battery production, and other clean energy technologies, leaving the rest of the world increasingly dependent on Chinese innovation and manufacturing to drive global energy transitions (United States Institute of Peace, 2023).

5.2 The United States

The United States Geological Survey (USGS) has designated 50 critical minerals as 'essential to the economic and national security of the US', 45 of which are also considered strategic minerals of interest by the Department of Defense, defined as 'those that support military and essential civilian industry' (USGS, 2022). Most importantly, China is the major source of US imports of 31 of these 50 critical minerals. China's dominance of global critical mineral production and processing capacity jeopardizes the United States' national and economic security (United States Institute of Peace, 2023). In 2023, China announced export controls on graphite, for which the United States is 100 percent reliant on imports from China, a response to the United States tightening artificial intelligence-related export restrictions to China (Way, 2024). Shortages of graphite could severely impact US production of batteries, fuel cells, nuclear reactors, and industrial applications.

To counter the Tanzania-Zambia Railway Authority (TAZARA) line built by China, linking the port of Dar es Salaam with central Zambia in the Critical Minerals Race, in 2023, the US announced an investment of USD 250 million in a rail line between the Angolan port city of Lobito and the Zambia/the DRC copper belt, known as the Lobito Corridor. This is the biggest US infrastructure investment in 40 years in Africa (Figure 32). The US-backed Lobito Corridor and the China-built TAZARA corridor are a dynamic race for the routes and raw materials that will power the next century's modes of transport. The United States and its African partners are betting that the corridor will attract enough users to be economically viable and that it will spur additional economic growth and investment, including robust minerals and agricultural development (Centre for Strategic and International Studies, 2024).

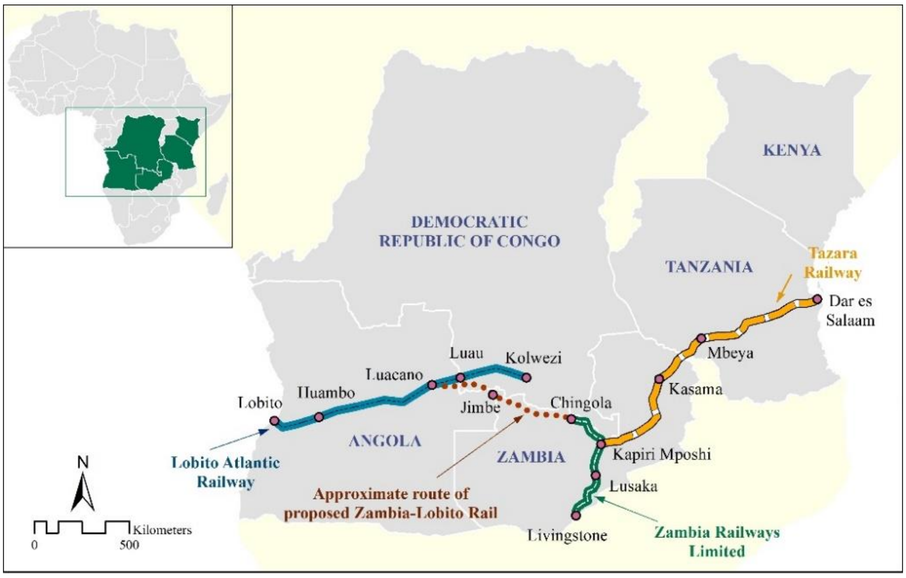


Figure 32. The US- and China-backed railway corridors from the copper belt to African ports. Source: United States Institute of Peace, 2024

5.3 Australia

Australia maintains two lists of minerals that are important for its modern technologies, economies, and national security. The minerals on the critical minerals list and strategic materials list mainly support the transition of Australia's economy to net zero emissions, advanced manufacturing, defense technologies, and other broader strategic applications (Australian Government, 2024). There are 32 critical minerals and another five minerals listed as strategic materials, including aluminum, copper, phosphorus, tin, and zinc.

Australian companies have shown a keen interest in a variety of natural resources including critical minerals (Africa's Investment Gateway, 2024). Australia's presence in Africa's mining sector is both extensive and growing, with over 145 Australian mining companies operating under five hundred mines across thirty-four African countries (Way, 2024). The significant economic presence of Australian mining in Africa demonstrates that continent's vast mineral wealth and highlights the strategic importance of Australian mining investments in Africa. With traditional advanced economies such as the US and emerging economies such as China, Turkey, and India rushing to Africa, a more genuine partnership is required by Australia, contributing to the deepening economic ties between the two regions (Australian Institute of International Affairs, 2022).

5.4 Canada

Critical minerals are strategic assets that contribute to Canada's prosperity and national security. Canada has listed 31 minerals that are currently considered to be 'critical'. They are used in various essential products, from mobile phones to solar panels, electric vehicle batteries, medical and healthcare devices, and military and national defense applications (Government of Canada, 2022). In 2024, Canada expanded its critical minerals list, adding high-purity iron, phosphorus, and silicon metal to the previous 31 minerals (Government of Canada, 2024).

Canada is significantly involved in African critical minerals extraction, investing heavily in exploration and development projects, focusing on cobalt, copper, and lithium (Way, 2024). The country has USD 37 billion worth of assets in African mining, with recently increased assets in the DRC, Mali, South Africa, Tanzania, and Zambia. Canadian companies in partnership with African enterprises, discovered promising copper reserves in northwestern Zambia in 2024, and have increased their asset value by over USD 622.1 million (Energy Capital and Power, 2024). In the DRC, Canadian companies have expanded their investments by USD 488.6 million. The African continent has become Canadian industry's second-largest investment destination after the Americas (African Business, 2024). Canadian firms are also advancing other critical minerals exploitation such as rare earth projects in Namibia and Malawi, strategically investing in critical mineral-rich countries to drive the global transition to clean energy technologies.

5.5 South Korea

South Korea's critical minerals strategy is to accelerate the development and diversification of supply chains to service South Korea's traditional economic priorities (Sharma, 2023). In 2023, the South Korean Ministry of Trade, Industry, and Energy (MOTIE) unveiled a strategy aimed at ensuring a consistent and secure source of critical minerals such as lithium, nickel, and rare earth materials (IEA, 2023). A list of 33 critical minerals and 10 strategic critical minerals were announced as a part of 'the measures for securing critical minerals supply'. This initiative was in response to escalating geopolitical uncertainties and developing global supply chain issues caused by the shifting dynamics between the US and China (Dickens, 2024).

At the same time, South Korea has significantly ramped up its efforts to establish a robust presence in the mining sector in Africa. In 2024, the South Korean government held its first summit with Africa in Seoul. The summit was attended by more than thirty African political leaders from countries that are increasingly seen as vital for South Korea's production of semiconductors, solar panels, and electric vehicle batteries (Reuters, 2024). Following the summit, the Korea-Africa Critical Mineral Dialogue was established to 'serve as an important institutional foundation for enhancing cooperation between Korea and Africa'. South Korean companies pledged $57.9 million USD in various commitments, and forty-seven agreements and memorandums of understanding were agreed including critical minerals cooperation with Madagascar and Tanzania (African Development Bank, 2024). By establishing this institutionalized summit with African countries and integrating critical minerals into the agenda, South Korea's objective is to protect its economic security via mineral security. To accomplish that, it is strengthening its strategic ties with Africa which will have a vital role to play (Sharma, 2023).

5.6 United Kingdom

In 2022, the UK government adopted its Critical Mineral Strategy, whose objective is to mitigate risks and make critical mineral supply chains more resilient through what it dubs an 'A-C-E approach' to critical minerals: Accelerate domestic capabilities, collaborate internationally (mainly to foster supply diversification) and enhance international markets (including increasing market transparency and responsible supply chains) (HM Government, 2022).

Similarly to the EU and the US, The UK is expanding its partnerships to secure critical minerals supply in Africa (Vandome, 2024). In 2022, the UK and South Africa agreed to a partnership on critical minerals for clean energy technologies. They have also agreed to hold a regular ministerial dialogue on critical minerals. Eager to diversify its supply chain, the UK has recently turned to Zambia, a major producer of copper, cobalt, manganese, and nickel (Way, 2024). The two nations entered into the Green Growth Compact, aimed at generating over $3.2 billion USD of British private-sector investment in Zambia's critical minerals and clean energy sectors, with an additional $650 million of government-backed investments (Way, 2024). Beyond forming partnerships with African countries, the UK is also pursuing partnerships with other nations looking to invest in critical minerals and curb Chinese influence in Africa (HM Government, 2023). In 2023, the UK and Japan established a framework to jointly invest in African mine development and to stabilize their mineral supply chains.

5.7 Japan

As a country with a scarce endowment of mineral resources but a very high capacity for technological development, Japan initiated an industrial policy for mineral reserves as early as the beginning of the 21st century. Japan imports 100% of almost all base metals and minor metals from overseas. Such commodities are essential for Japan's continued dominance in the car manufacturing industry and the electrical appliances industry (Najah, 2024). In recent years, Japan has become increasingly dependent on China for its critical minerals to produce electric vehicle batteries and clean energy. To reduce its reliance on China, diversifying the sources of critical minerals supply is especially important to Japan.

As African countries are gaining importance and influence on the international stage, Japan aspires to be a collaborative partner, fostering mutual growth with Africa. Japan has signed contracts with three African countries, Namibia, Angola, and the DRC (Japan Organization for Metals and Energy Security, 2023). In the DRC, Japan has committed to investing $1 billion USD to explore rare minerals in this country rich in cobalt, lithium, and copper. In Zambia, a memorandum of understanding was signed to develop exploration and exploitation operations by Japanese companies, to achieve an annual copper production of 3 million tons (The Africa Report, 2023). In Namibia, Japan Organization for Metals and Energy Security signed an MOU with the Ministry of Mines and Energy of Namibia for cooperation in supply chain research to promote the development of rare earths, training in metallic mineral resource exploration technology, and other joint analyses (Japan Organization for Metals and Energy Security, 2023).

5.8 European Union

Raw materials are foundational for the EU's strategic sectors of clean energy, e-mobility, energy-intensive industry, ICT, aerospace and defense. Europe is fueling its demand for nickel, lithium, and other transition minerals to support its industries in profiting from the energy transition. In 2023, the European Commission established the Critical Raw Materials Act (CRMA), outlining a series of measures related to international trade, including signing strategic partnerships with several emerging and developing economies and using trade agreements to secure access to critical minerals (European Commission, 2020). These partnerships with resource-rich countries in the Global South are announced as 'mutually beneficial', focusing on sustainable and responsible production in the sourcing of critical minerals and enhancing local value addition in these countries.

Africa is currently a leading exporter of at least 10 critical minerals to the EU and European policymakers have announced several Strategic Partnerships agreements to enhance cooperation with mineral-rich countries across the continent. Launched by the European Commission and other partners in 2020, the Strategic Corridors and Urban Systems for Africa (CUSA) initiative aims to support the creation of strategic, sustainable and secure transport corridors and support value chains, services and jobs that can benefit industries in both Africa and Europe (Baranzelli et al., 2022). Five of the corridors are situated in the areas covering 49 percent of the critical minerals reserve (i.e. aluminium, beryllium, caesium, chromium, cobalt, copper, graphite, lithium, etc.). These so-called EU- Africa strategic resource corridors aim to mitigate the risk of supply disruptions of critical raw materials for the EU. The CRMA, constrained by financial and ideological limitations, presents a distinct approach when compared to US subsidies and China's state support for Africa's critical minerals. Criticisms of this EU strategy argue that this partnership is focused on reducing reliance on sole suppliers rather than on how it could support the creation of new supply chains for metals and minerals processing in Africa (Vandome, 2024). Whether African countries perceive CRMA as an opportunity and benefit for moving up their critical mineral value chains remains to be seen.

6. Challenges for critical minerals extraction and implications for Africa's structural transformation

As countries and regions seek to grow their clean energy technology production capacity, securing sufficient and reliable supplies of critical minerals has become an increasingly strategic concern. The production and processing of critical minerals is highly concentrated geographically, posing challenges related to resource security and geopolitical dynamics (Boafo et al., 2024). Concentrated supply chains in critical minerals could be problematic or trigger disputes because intentional disruptions could affect a country's industrial competitiveness and provide economic and political leverage to suppliers with market power (Nakano, 2021). In Africa, the current discourses on critical minerals have been mainly shaped by geostrategic and economic opportunities arising from demands from Western countries and China rather than what supply chains African countries must secure for their industrial development. Understanding potential challenges and implications for Africa's structural transformation is essential for Africa to enhance productivity against this geopolitical shift.

6.1 Challenges for critical minerals extraction for Africa

The number of advanced and emerging economies seeking to enhance their competitiveness along the critical minerals supply chain is growing. China's midstream and downstream capacities development has turned it from a supplier of raw minerals and materials to a key consumer. China's commanding position along critical minerals supply chains is a key factor that shapes the strategic responses of other economies (Lu, 2024). Several economies have updated their strategies, expanding policy tools to address the challenge, or introducing action plans to improve or preserve the security of critical minerals supply chains. Moreover, many countries aim to localize critical mineral supply chains, but adjusting these supply chains necessitates careful balancing of economic factors, environmental impacts, and the well-being of local people (Brown, 2018). Therefore, the centralized supply chains for many critical minerals will likely remain as they are for the foreseeable future.

The African continent is becoming a battlefield in the race between developed and emerging economies to secure their supply of critical minerals (Andreoni and Roberts, 2022). Many African countries currently operate in the upstream segment, extracting minerals and exporting raw materials without substantial value addition. This perpetuates the continent's position on the lower rungs of global value chains, constraining economic benefits and the ability of African countries to negotiate favorable trade terms. Apart from that, the extraction of critical minerals in Africa is already plagued with corruption and various related socio-economic and environmental governance challenges. Mining of critical minerals is water use intensive, with extensive environmental impacts such as air pollution, deforestation, soil degradation, and biodiversity loss (UNEP, 2020). Moreover, in places where labor standards are weak, working conditions can be very harsh, and child labor is also rampant. Such countries, including the DRC, Zimbabwe, and Namibia, are at serious risk of transnational corruption and environmental degradation. These governance challenges underscore the utmost importance of ensuring effective community engagement to ensure that benefits from mining investments flow into surrounding communities by, for example, providing jobs and healthcare, skills training and road construction (Ayuk et al., 2020).

Many African countries have historically not managed the proceeds from exploiting their natural resources well. The new geopolitical environment of appropriating critical minerals may make things worse. If the primary interest of external partners remains the sourcing of critical minerals from Africa without complementary investments in domestic processing or environmental and social sustainability, the growing demand for critical minerals is unlikely to result in a mutually beneficial outcome for Africa (Kelley et al., 2021). There is a strong interest in Africa to leverage the region's mineral wealth to transform economic structures and support jobs and economic growth through industrialization.

6.2 Implications of critical minerals extraction for Africa's structural

Economic transformation and structural change are the essence of economic development in most developing countries. Economic development only happens when there is a fundamental structural transformation in the economy's productive structure and the underlying capabilities that make that productive transformation possible (Chang, 2002, 2018). Although the growing demand for critical minerals from Africa has increased exploration and mining activities, studies have identified that structural change has typically been growth-reducing in countries with a relatively large share of mining outputs in exports of natural resources (Martins, 2019). Additionally, the criticality changes over time, depending on technological innovation, market volatility, and consumption demands. The so-called critical minerals of today are not necessarily the critical minerals of the future. If African countries could not be transformed by harnessing their natural resources such as oil, gas and iron ore in the past, what are the differences in this new wave of natural resource exploitation of critical minerals for energy transitions? What are the key determinants of Africa's structural change in leveraging critical minerals?

The production system, shifting towards higher value-added and higher productivity activities, has historically evolved in many stages, from the Pin factory to the global value chain (Chang, 2019). The pathway of minerals from mines to finished products involves a complex and often opaque network of actors and processes. Intra-African value chain integration could reduce dependency on unprocessed goods and natural resources as exports and increase resilience to supply chain shocks (Andreoni and Avenyo, 2023). Moving up the value chain of critical minerals is politically, socially, and economically appealing but challenging for natural resource-rich countries in Africa (Müller et al., 2023). 'Missing links' and low use of inputs from the continent are the two weaknesses in higher value addition. For example, in the automotive value chain, Africa has a trade surplus in copper alloys, amounting to €6.7 billion of net exports, but 93% of these copper alloys are exported to other continents and processed into copper wire mostly in Asia and Europe. Thus, African producers, mainly Morocco, Tunisia and Egypt, import copper wire and transform it into insulated wire. Then they export it, with a trade surplus of €1.9 billion. Importing the final products, cars and components, Africa has a trade deficit, with net imports of €5.9 billion and €1.8 billion, respectively (ITC, 2022). The case for developing the automotive value chain is further reinforced by its linkages with other promising subsectors, such as leather and leather products and batteries. Enhancing the linkage of these sectors will be very helpful to fully realize an economic transformation in Africa. A continent-wide strategy is a prerequisite to enhance the linkage crossing countries.

The structural transformation of the agricultural sector has been characterized by the growing share of high-value agrarian products in agro-related industries and agricultural trade. This process has been primarily driven by improvements in productivity and changes in production activities. Across sub-Saharan Africa, over 60% of the population lives in rural areas, and agriculture remains the dominant source of employment. However, the lack of access to affordable fertilizer is an acute constraint to enhancing Africa's crop yields (Chang, 2012). Increasing the use of lower-cost sources of mineral fertilizers is recognized as one of the main ways to enhance crop yields in Africa. Critical minerals are essential in raising agricultural productivity due to their direct link in supplying the raw materials necessary for a wide range of inputs (such as fertilizer) and other consumables (such as copper-based fungicides). For example, phosphorus and potassium are minerals that are essential in producing fertilizers. Zinc, boron, manganese, iron, copper, and molybdenum are essential for plant health, and are often applied as foliar sprays or added to the soil. To use fertilizers intensively, easier road access for farmers to the domestic market, the removal of nontariff trade barriers for high-value agrarian products to the international market (such as sanitary, phytosanitary, and technical standards), and setting the proper regulatory framework are all vital to improving agricultural productivity (Weng et al., 2013).

Transformations extend beyond the narrowly defined economy. By placing these transformations centrally in the understanding of growth, long-lasting debates reflect that 'economic development' is not only equivalent to growth in per capita income but also to qualitative change (Chang, 2018). Growing evidence suggests that human capital is important in promoting structural change. Improved skills and knowledge enable workers to move to more productive jobs, and good physical health and cognitive functions may contribute to structural change (Gollin and Kaboski, 2023). The extraction and processing of critical minerals in the mining industry could catalyze socio-economic development in Africa. The primary debate in society, especially in resource-rich developing countries, is how the wealth generated by natural resources should be distributed for benefit sharing with communities. One of the main benefits the mining sector can bring to local communities affected by mining activities is employment generation (Fleming and Measham, 2014). Studies have indicated that if regions can maintain and expand local firms specializing in dealing with inputs and outputs of mining industries, or if local entrepreneurs can innovate to generate new products and processes related to the resources industry, job spillovers can be positive without labor crowding out potentially happening in manufacturing firms (Martins, 2019; Fleming and Measham, 2014).

Finally, structural transformation has been recognized as a critical mechanism for improving living standards in developing countries (Chang, 2018). However, such change can be associated with considerable environmental damage and challenges sustainable development. The mining industry's frequently severe environmental impacts highlight the necessity of carefully balancing mining activities with stewardship of other valuable natural resources, including water, forests, and other components of biodiversity such as ecosystems, habitats and species (UNEP, 2020). Governance has been recognized as pivotal in mitigating the adverse impacts and enhancing the mining industry's positive economic, social, and environmental outcomes. However, the governance issues are multiple and interlinked, cutting across sectors and engaging both government and non-government entities. The imperatives of investors further complicate it as they consider long life cycles from upstream to downstream investments and in the context of unpredictable commodity cycles and asset fixity (Boafo et al, 2024). Chang argued that increased wealth intensifies the demand for, and provision of, higher-quality institutions and new political actors who shape them (Chang, 2011). In that sense, coordinating governance among different actors in the mining industry is imperative for increased economic prosperity and environmental protection (Ayuk et al., 2020).

7. Conclusions

African countries have the poorest and least diversified economies in the world. Industrialization has been limited, and in general, the changes that have taken place are minor relative to what would be needed for large-scale transformation. Compared to most other regions of the world, Africa's structural transformation still lags far behind. The slow pace of structural transformation across most African countries today is due to low productivity levels, weak linkages between sectors, poor integration of natural resources related to agriculture and mining into channels of value-addition, and poor integration of African firms into higher-value functions of global production networks.

Critical mineral exploitation remains a crucial aspect of African development and global trade networks, and it is essential for emerging technologies, clean energy, digitalization, and advanced manufacturing. Participation in the critical minerals industry presents opportunities to drive industrial development and structural transformation across the continent, necessitating the creation of horizontal and vertical linkages across sectors. However, disruptive technological innovation is adding to the uncertainty of future demand for critical minerals. The world needs the critical minerals that Africa has today, but that may not be the case tomorrow. Developing industrial capabilities by adding value to critical minerals within country, is essential for Africa to help eradicate poverty and sustain their social-economic prosperity.

The market will not automatically and efficiently facilitate any required reallocation of resources across mining sectors. African governments must create an enabling environment for investment in terms of tax incentives, industry cultivation and effective management of revenues for relatively equal distribution generated from mining industries. This requires a holistic approach developed by multiple stakeholders, involving governments, private sector actors, and civil society, which is essential to avoid the 'resource curse' and ensure that the exploitation of mineral resources benefits both the economy and local communities.

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