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The Impact of the Energy Transition and Sustainable Development Goals on Mineral Resource Availability in Africa

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Abstract

Understanding and predicting the impact of the global energy transition and the United Nations Sustainable Development Goals (SDGs) on global mineral demand and African supply is challenging. This study uses a resource nexus approach to investigate and analyze the impact of this transition on energy and water demand and CO_2 emissions using three annual material demand scenarios. The results indicate that African mining will consume more energy by 2050, leading to an increase in cumulative demand for energy (from 98 to 14,577 TWh) and water (from 15,013 to 223,000 million m^3), as well as CO_2 emissions (1318 and 19,561 Gg CO_2e). In contrast, only a modest increase in energy demand (207 TWh) will be required by 2050 to achieve the SDGs. Therefore, the African mining industry should reduce its energy consumption and invest more in the renewable energy sector to support the global energy transition.

Keywords

Mineral-Energy Nexus, Climate Change, SDGs, African Mining Industries, Energy Transition

1. Introduction

The adoption of renewable energy sources is an important step in combating climate change and promoting sustainable development [1]. This transformation has significant implications for energy development and achieving Sustainable

Development Goals (SDGs) in Africa, a continent with unique energy challenges and opportunities. SDG 7, which aims to ensure access to affordable and clean energy, requires the adoption of renewable energy technologies [2]. However, this transition may have unintended consequences for other SDGs [2]. Effective climate finance strategies are required to support sustainable development efforts in Africa, and overcoming regulatory, institutional, and market barriers is critical [3]. Multinational energy companies use various tactics to integrate renewable energy, which impacts the economy, the environment, and society [4]. Despite progress in some regions, sub-Saharan Africa is still struggling to meet its renewable energy target [3]. To address these challenges, sub-Saharan African nations must develop and implement effective renewable energy policies tailored to each region's specific context and needs [5]. The study adopted a multidisciplinary approach to evaluate the association between African energy policies, environmental initiatives, and sustainable growth. It is widely recognized that modifications in energy systems are essential for reducing greenhouse gas emissions and achieving Sustainable Development Goals (SDGs). However, these changes may not be sufficient to address the specific objectives of affordable and clean energy and climate action in Africa [6]. The transition towards renewable energy sources could result in unforeseen environmental consequences and hinder progress toward specific SDGs [7]. Furthermore, although green taxes may offer benefits for environmental protection and revenue generation [8], they could also exacerbate inequality and energy poverty, which could undermine other SDGs.

Increasing global population and economic activities have raised concerns about the sustainability of resource management and environmental impacts [9] [10]. Advancements in solar power, wind energy, electromobility, and energy efficiency present challenges for energy and water systems [8]. As a result, various studies have explored potential scenarios for the global energy transition and the material-energy nexus [11]-[14]. The increasing demand for Minerals required for human activities may necessitate additional mining activities and higher energy requirements in producing countries [15]. It is crucial to implement robust policies, investments, and sustainable infrastructure to promote the development of green energy and stimulate economic growth [16]. However, extracting minerals for energy transition may pose risks and trade-offs that can harm the environment and displace local populations. Although Africa is rich in mineral resources, poor management has hindered sustainable socio-economic development [17]. African countries face varying levels of access to energy, with some regions, such as North and South Africa, having clean and electrified energy, while West Africa lacks access to electricity for millions of inhabitants [17]. Additional measures beyond energy policies may be necessary to achieve the energy transition objectives in Africa [3]. The main focus of this study is on the scenarios that may occur in mineral-producing countries regarding supply.

Addressing climate change impacts in sub-Saharan Africa highlights the importance of resilience strategies to mitigate extreme weather events and achieve

Sustainable Development Goals [18]. Inefficient resource allocation and mismanagement during mineral extraction can impede sustainable development in Africa [3]. Obtaining and preserving energy and mineral resources is essential for economic growth and improved living standards, although increased mineral production may conflict with energy and water resource conservation efforts [12]. Adopting a nexus approach that explores the interrelationships among energy, minerals, ecology, economy, and society can aid in identifying energy and material exchanges across regions. Research on energy technologies' mineral and climatic implications is vital for promoting sustainable growth in Africa.

This study aims to 1) evaluate the current mineral and energy demands, analyze the implications of the global energy transition on mineral supply, and 2) assess the consequences of rising mineral demand on energy and water requirements in Africa. This study 3) examined the impact of transitioning to renewable energy sources on achieving sustainable development goals (SDGs) and mitigating climate change in Africa. This study offers essential information to policymakers and development planners for areas that require immediate attention and contributes to the scientific understanding of the impact of the global energy transition on energy development and climate change in Africa. The structure of the paper is as follows: The introduction and literature review present the background and objectives. Section 2 provides information on the study area, the analysis strategy, and the methods employed for data collection. Section 3 presents and discusses the results, and the conclusion closes the study.

2. Literature Review

Minerals, energy, water, and climate have attracted significant scholarly interest in Africa's sustainable development [14]. Studies emphasize the importance of water, energy, and food security interdependencies for sustainable development, particularly as climate change threatens these sectors [3] [14]. The Horn of Africa faces challenges in achieving Sustainable Development Goals related to hunger, clean water, and affordable clean energy [19]. Transitioning to renewable energy is crucial for attaining clean energy and climate action goals, positively affecting the economic, environmental, social, and institutional aspects of Africa [20]. Investigating the connection between renewable energy and poverty reduction is a primary research focus that shapes sustainable energy development and resource policies across nations. Mineral extraction, particularly in sub-Saharan Africa, significantly impacts the environment through greenhouse gas emissions, necessitating sustainable industrial practices [21]-[24]. Despite the correlation between industrial growth and increased CO_2 emissions, adopting renewable energy and efficient technologies can mitigate these effects [25]. The energy-intensive nature of mineral processing exacerbates environmental degradation, and countries with abundant minerals face the challenge of balancing economic development with environmental concerns [3]. The interplay among energy consumption, economic growth, and carbon emissions highlights the need for eco-friendly extraction methods and stringent environmental regulations. Economic growth driven by Africa's energy transition can help reduce the environmental impact of energy use, emphasizing the importance of focusing on economic growth and productive energy usage [26] [27]. Adopting circular economy principles is recommended to address environmental, social, and economic challenges and advance Sustainable Development Goals (SDGs) [28]. Renewable energy adoption improves air quality and contributes to achieving sustainable development targets, particularly for poverty alleviation [29]. Advancing is increasingly emphasized across various sectors, including energy, business growth, poverty reduction, and information and communication technology.

The energy sector, particularly water infrastructure, consumes significant electricity in regions such as South Africa, where load shedding manages the electricity demand [3]. Transitioning to renewable energy is vital for reducing environmental impacts and achieving Sustainable Development Goals (SDGs) related to clean energy, economic growth, and climate change [30] [31]. The water-intensive nature of mineral extraction requires decoupling from energy systems to ensure energy security and sustainability [32]. Policy, fiscal measures, and governance are crucial to achieving health and environmental sustainability in the mineral extraction sector. Africa's mineral extraction industry is complex and sustainable practices are essential for balancing industrial growth with environmental sustainability. Integrating renewable energy and climate change mitigation technologies is necessary to reduce greenhouse gas emissions and achieve the SDGs related to climate change, clean energy, industry, innovation, and infrastructure. Sustainable mineral extraction and energy consumption practices are vital for mitigating the impacts of climate change in Africa and for achieving sustainable development goals. **Appendix Table A1** presents studies on mineral requirements in energy technology, SDG implementation, and the need for a nexus approach to decision-making and policy development.

3. Study Area and Methodology

3.1. Boundary Descriptions

The mining industry in sub-Saharan Africa is an interesting topic, with studies focusing on various aspects such as mineral dependence, energy consumption patterns, and water use. The African continent is home to 80% of the world's industrial minerals and metals, with the Congo, the Kalahari, and crystalline rocks being the most important cratons. Countries such as the Democratic Republic of Congo, Guinea, Mozambique, South Africa, Zambia, and Zimbabwe were selected for their significant mineral deposits and energy technology needs (**Figure 1**). However, the sustainable development of the mining sector in these countries remains a subject of debate and concern due to the resource-intensive nature of the industry and its impact on the environment and local communities [33]. Africa is rich in natural resources and has significant potential for renewable energy and sustainable development, making it a key player in the global energy transition and the Sustainable Development Goals. To address climate change and support sustainable development, effective climate finance strategies are required to support renewable energy projects in Africa [34] [35]. The present study did not include the artisanal mining operating process. Instead, the assessment focuses on industrial mineral extraction and supply steps because the refining process is mainly outside (**Table A2**).

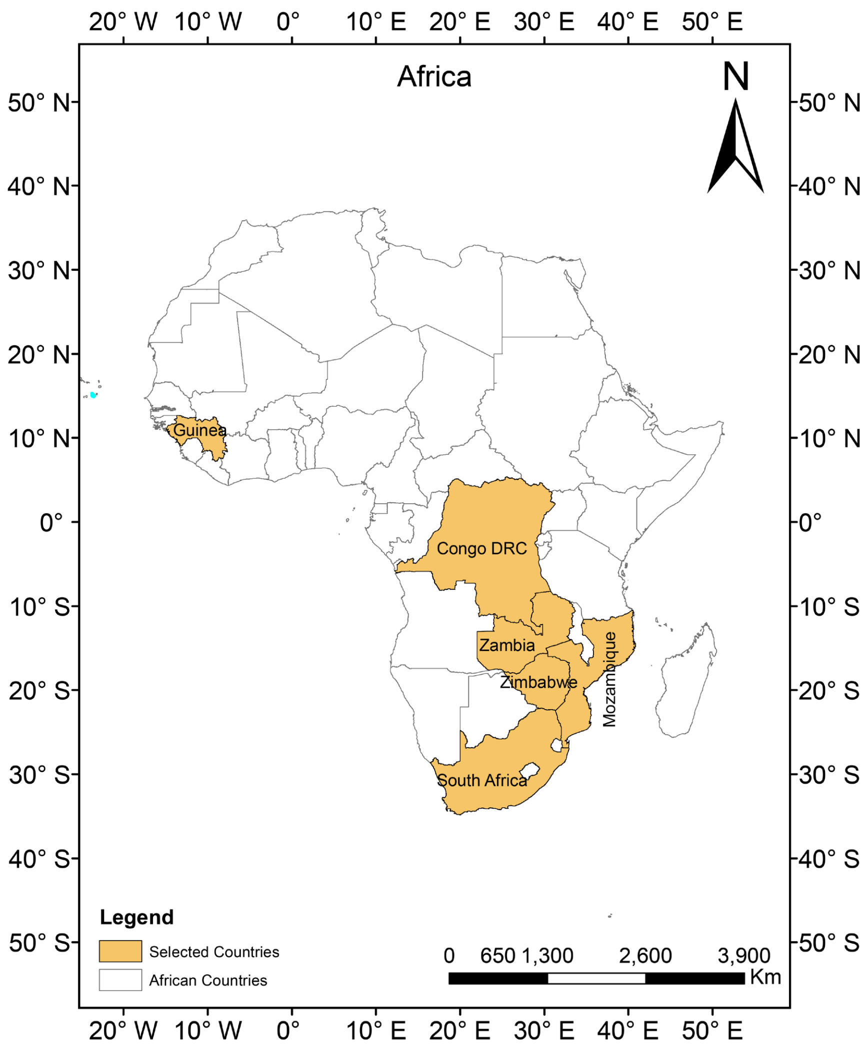


Figure 1. Study areas.

3.2. Collecting Minerals Demand, Energy, Water, and CO_2 Data

Forecasts for renewable energy production, primarily from wind and solar energy, point to significant growth from 400 to 12,000 TWh by 2035 and 25,000 TWh by 2050, as reported by Vidal *et al.* [36]. This increase in energy production is expected to lead to an increase in demand for metals such as aluminum (310 million tons), copper (40 million tons), steel (3200 million tons), and other minerals [37]. Demand for these resources is expected to increase by an average of 5% to 18% annually over the next 40 years [36]. The current annual increase in global demand for ferrous, base, and minor metals, which amounts to around 5%, is being driven by both developed and developing countries, resulting in a surge in demand that is expected to further increase production levels. However, additional work is needed to estimate the amount of global mineral resources needed to support the growth of energy technology and infrastructure [38].

This study proposed a predictive model based on the estimated growth rates of minerals proposed by Vidal *et al.* [36]. To further validate the robustness of the model, the study planned to conduct three scenario analyses to assess the environmental impact of different levels of growth in global mineral demand. Specifically, the analyses examined a minimum increase of 5%, a maximum increase of 18%, and an average increase of 12% in annual mineral demand. These projections correspond to projected values for 2050 and provide a comprehensive understanding of the potential range of environmental impacts associated with different growth rates (**Figure 2**).

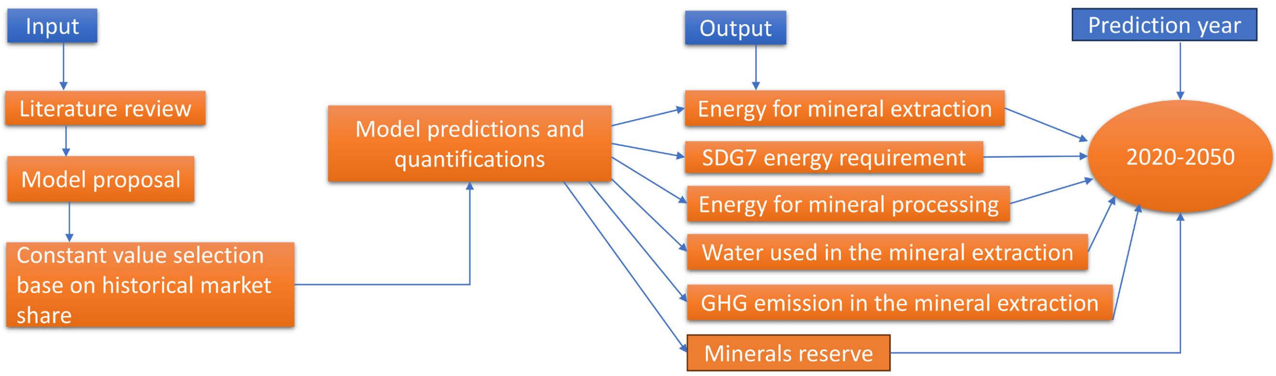


Figure 2. Flow chart of the research methodology.

By conducting these scenario analyses, this study can assess the sensitivity of the predictive model to different rates of mineral demand growth and provide valuable insights to policymakers and stakeholders on how to manage the environmental impacts of increased mineral demand, as shown in **Table A3**. This method is comparable to the work of Slameršak *et al.* [39], who developed three different EROI scenarios to illustrate a range of potential transitions, considering energy consumption and CO_2 emissions from the extraction-to-refining boundary. Although historical information regarding mineral market share can be beneficial for predicting future trends, it is crucial to consider factors such as market dynamics, technological advancements, and changes in consumer behavior that may affect the predictive accuracy of historical data. In this study, the 2020 market share was used to estimate the future African mineral supply (**Figure 3**), and a constant value for mineral reserves in 2020 was considered to calculate the years of mineral reserve production and anticipate the influence of growth in annual mineral demand on yearly production levels.

Meeting the increased demand for Minerals associated with the energy transition takes much work. The need for energy related to the extraction process was determined based on the annual mineral production using the above three minerals' scenarios from 2020 to 2050. Table 1 summarizes the energy allocated to mining compared to the current energy use from different sources (hydropower, solar, wind, gas, and oil).

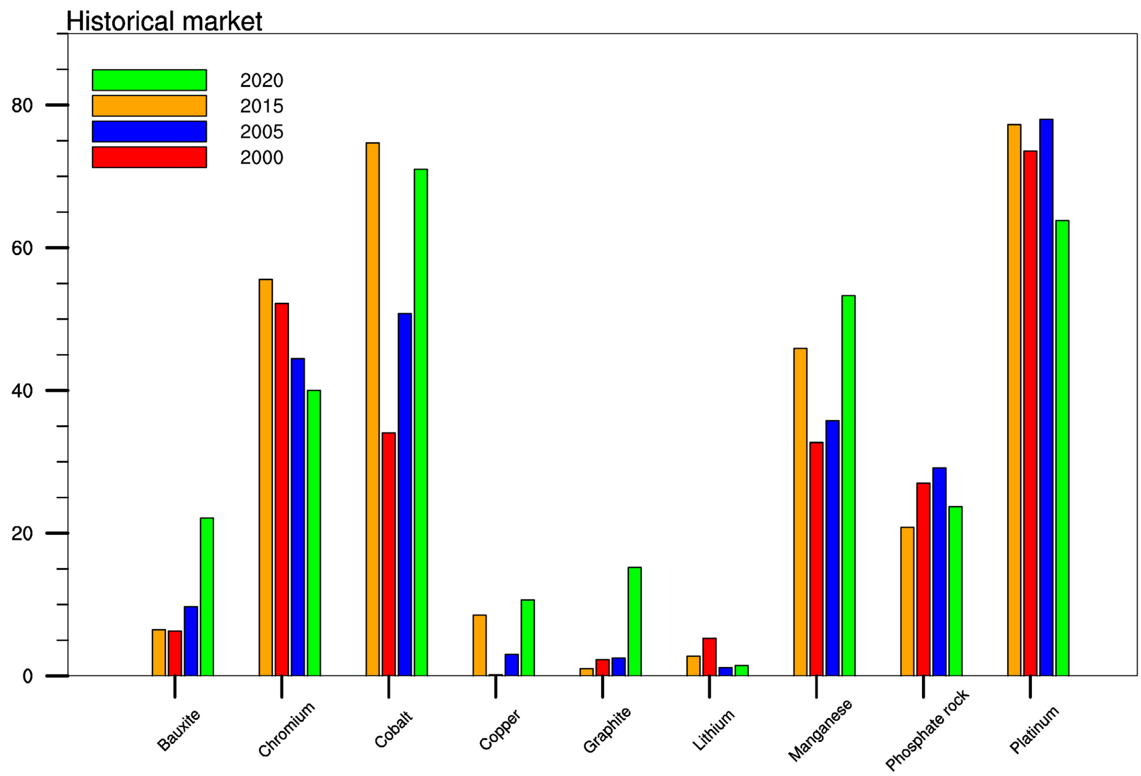


Figure 3. African market share in mineral supply (https://www.statista.com/).

Table 1. Energy capacity and CO_2 emissions in 2018 and 2019 energy share to mining in the selected countries.

Energy	Zimbabwe	Zambia	South Africa	Mozambique	Guinea	DR Congo
Production (TWh)	6800	11,550	234,500	18,390	598	9050
Local Consumption (TWh)	7120	11,040	207,180	11,570	556.10	7430
CO_2 Emission (mt)	12.27	7.74	433.25	6.64	3.12	2.20
Share of Mining (TWh)	260	2400	6900	160	1500	5600
Numbers of Mining	3	10	33	3	2	13

Source: https://www.worlddata.info/africa [40].

Finally, the producer countries' future energy needs for additional local mineral extraction or processing were estimated based on the energy conventionally required to extract or produce one unit of metal [40]-[43]. The energy demand for achieving SDGs based on each selected country's energy per capita and the population growth rate was obtained from the World Bank and IEA [44] [45] reports. This demand was then compared to the energy consumed in mineral extraction to determine the challenges linked to their SDGs and the existing energy, capacity of Africa.

In this study, data collection on water use in mineral extraction or processing was focused on bauxite, Co, Cu, Li, Mn, and Pt (**Table 2**) because information on the specific amount of water used to extract or produce Cr, graphite (a crystalline form of carbon), and phosphate rock was not available. The water demand for mineral extraction and production in each scenario was estimated and expressed as the increase in water until 2050.

Table 2. Average annual water consumption.

Minerals	Average water used (m^3/t)	Processing stages
Bauxite	0.447	Processed ore
Lithium	2,200	
Cobalt	208.4	
Copper	43.235	Concentrate
Manganese	1.404	
Platinum	313,496	

Source: [46].

Mining operations often necessitate using engines, fuels, and extraction equipment that release CO_2 [47] [48]. Therefore, this study focuses primarily on the CO_2 emitted during mineral extraction from the deposit to estimate the yearly increase in CO_2 emission based on the rise in annual mineral demand according to the proposed scenarios (**Table 3**).

Table 3. CO_2 emissions from mineral extraction.

Minerals	Average emissions	Units	Sources
Bauxite	4.9	(kg CO_2/t)	[47]
Manganese	3.24	(kg CO_2/t)	[49]
Phosphates	220.9	(kg CO_2/t)	[50]
Platinum	34	(t CO_2e/kg)	[51]
Cobalt	11.3	(kg CO_2/t)	[52]
Copper	3.7	(kg CO_2/t)	[47]
Chromium	5.8	(t CO_2e/t)	[53]
Lithium	15	(t CO_2e/t)	https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries#
Graphite	4.9	(kg CO_2e /kg)	[54]

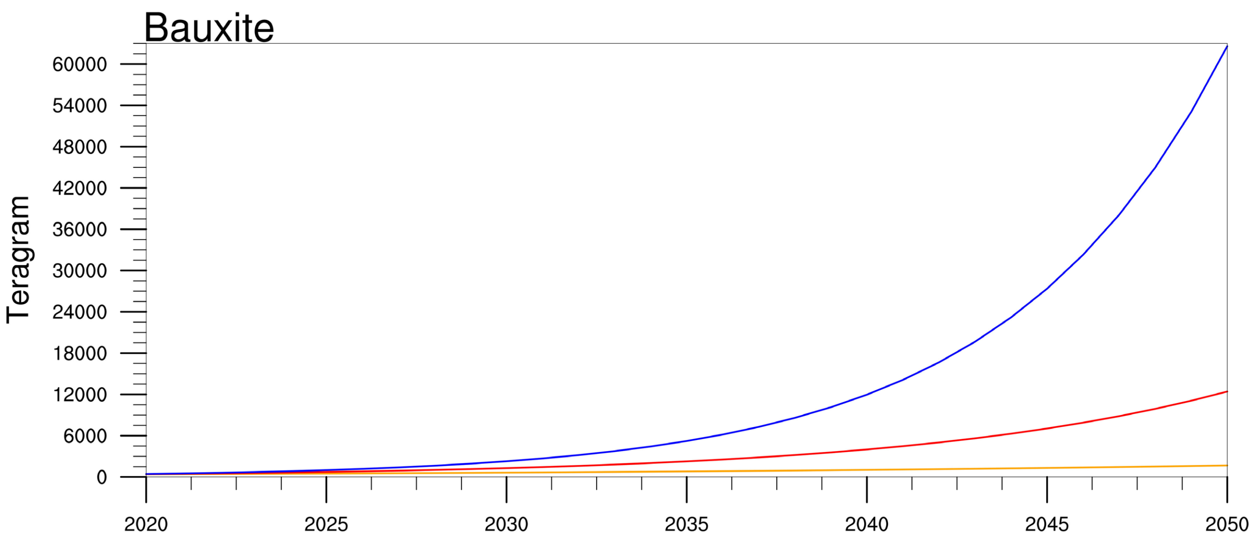
4. Results and Discussions

The following section reports and discusses the effects of the global energy transition on Africa's mineral supply and the possible consequences on energy, water, and climate change.

4.1. Cumulative Mineral Demand in the Global Energy Transition

Figure 4 provides a comprehensive summary of the anticipated escalation in the cumulative mineral demand for bauxite, chromium, Co, Cu, graphite, Li, Mn, phosphate rock, and Pt, based on the three scenarios. The results highlight an increased demand for bauxite, phosphate rock, chromium, manganese, cobalt, copper, graphite, and lithium following closely behind. These findings are consistent with the results presented in Table A4 and align with the projections reported by Koning *et al.* [55] for the increase in metal demand from 2011 to 2060 under the BAU, Techno, BMES, and REM 2050 scenarios.

The analysis revealed that the cumulative demand for bauxite, phosphate rock, chromium, and manganese by 2050 ranges from 27,500 to 400,000 teragrams (Tg), 17,832 to 264,599 Tg, 3270 to 48,510 Tg, and 1412 to 20,947 Tg, respectively. In the 12% and 18% scenarios, the global cumulative mineral demand for all minerals,



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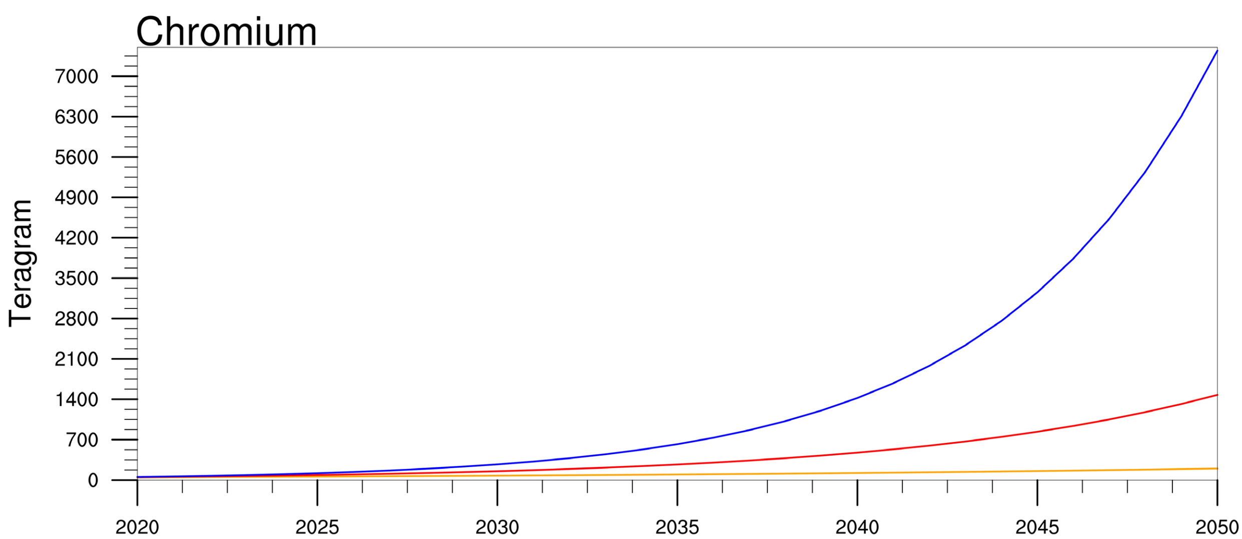

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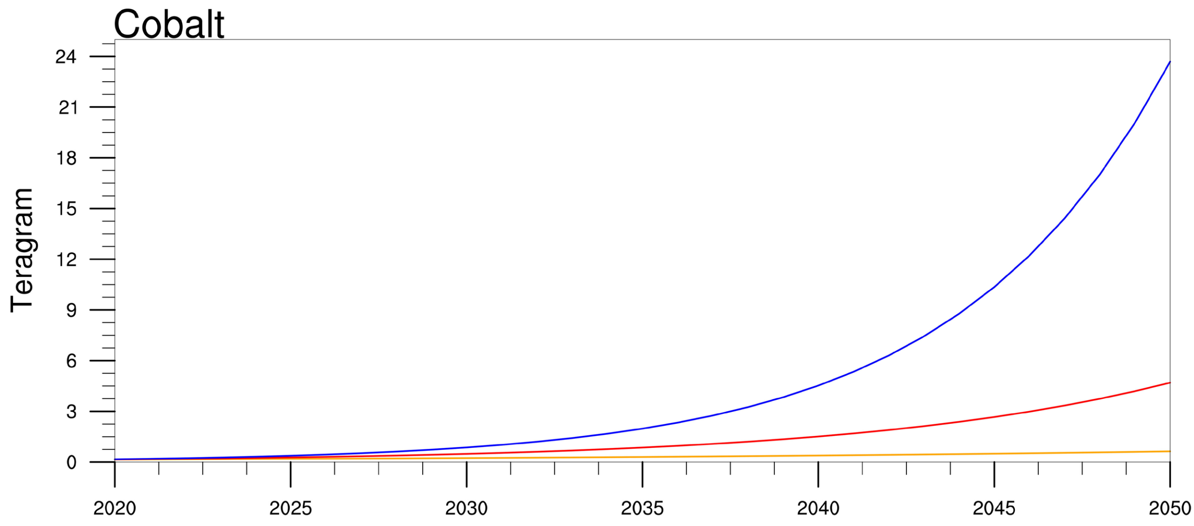
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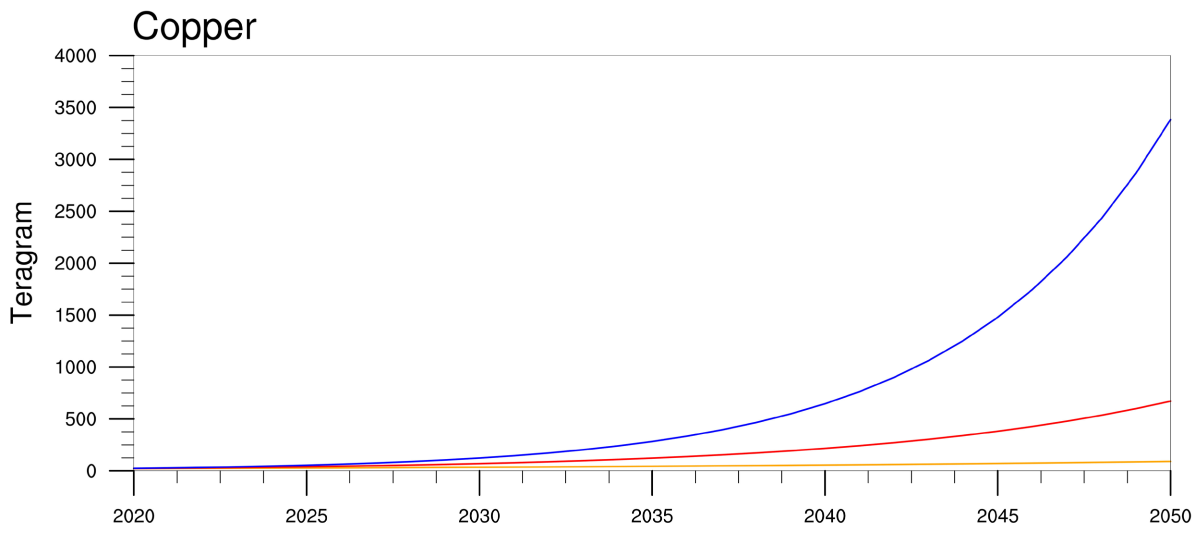
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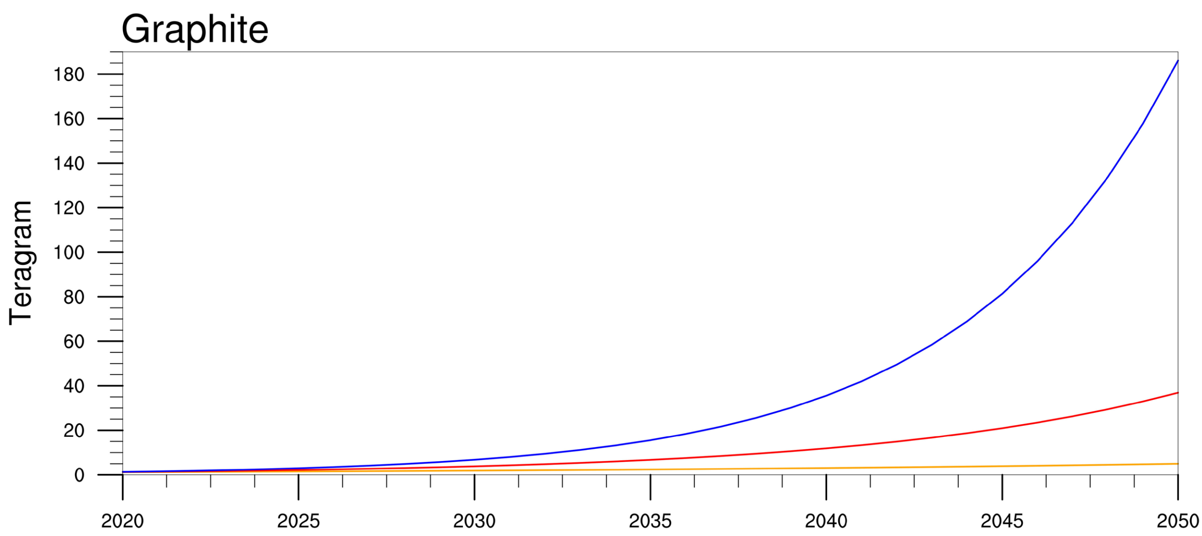
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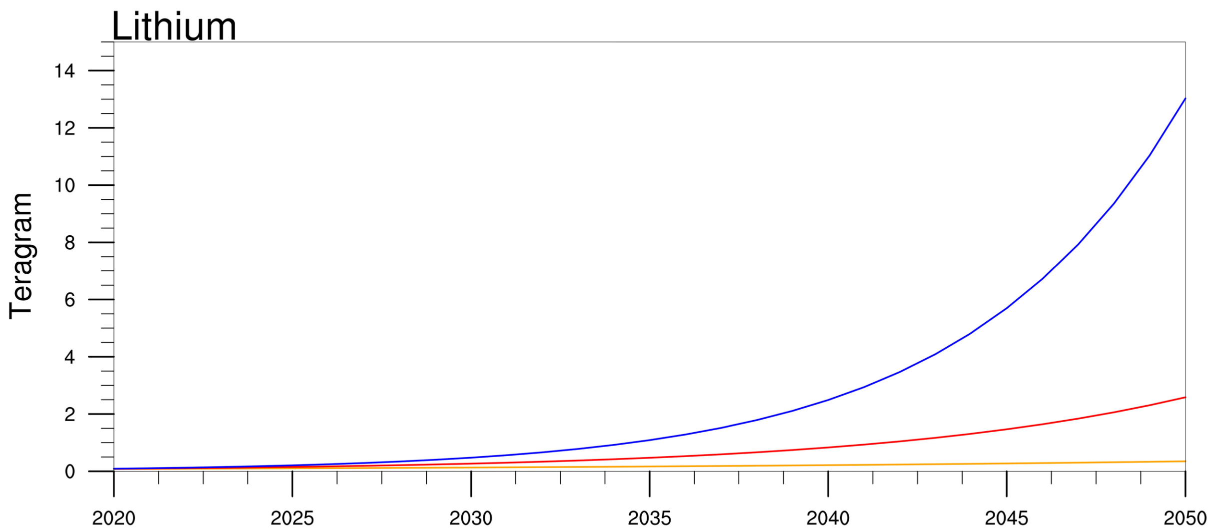
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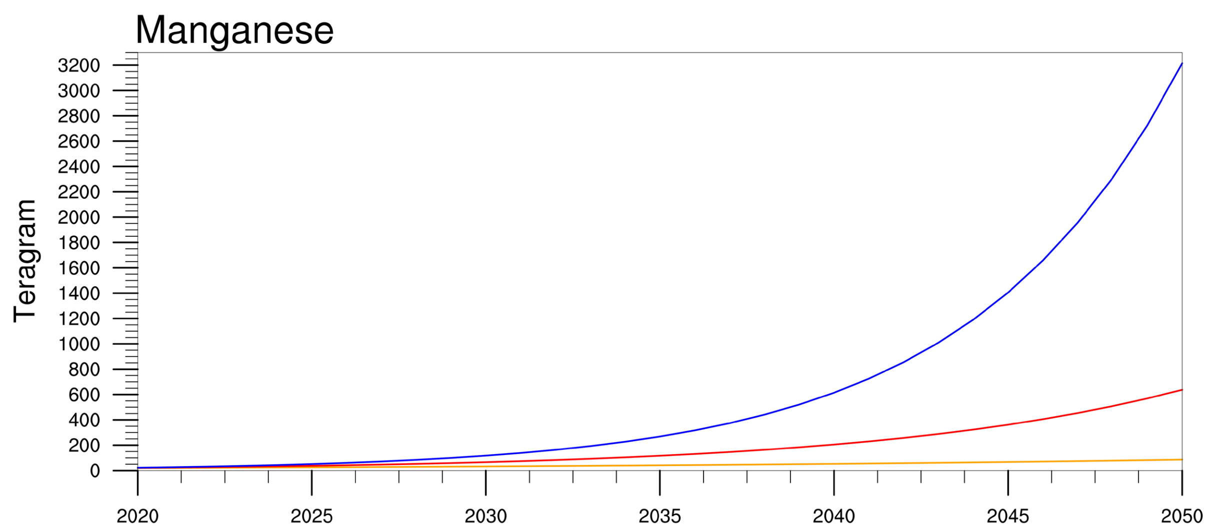
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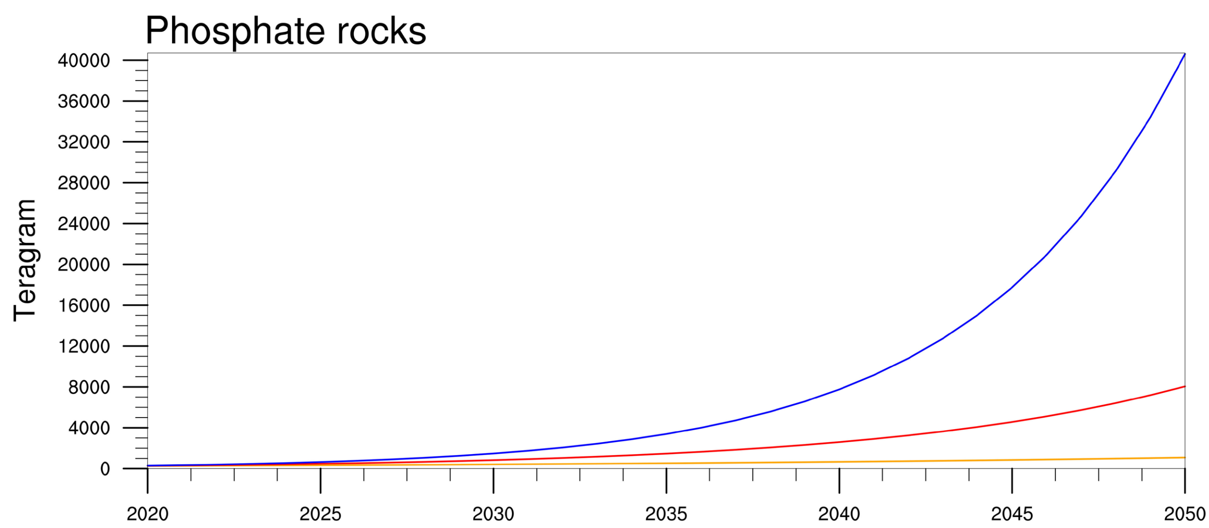
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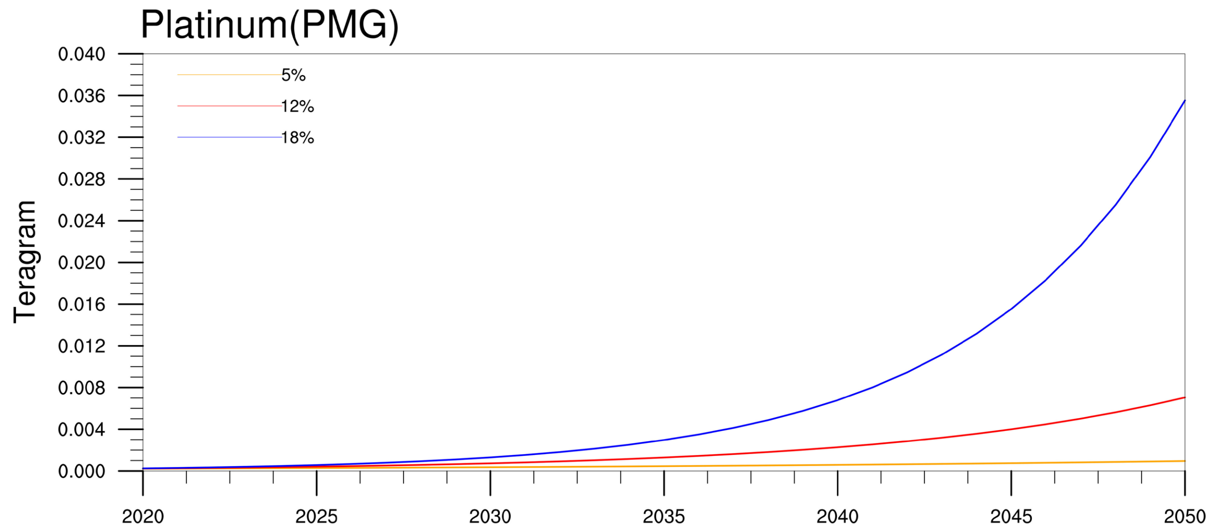


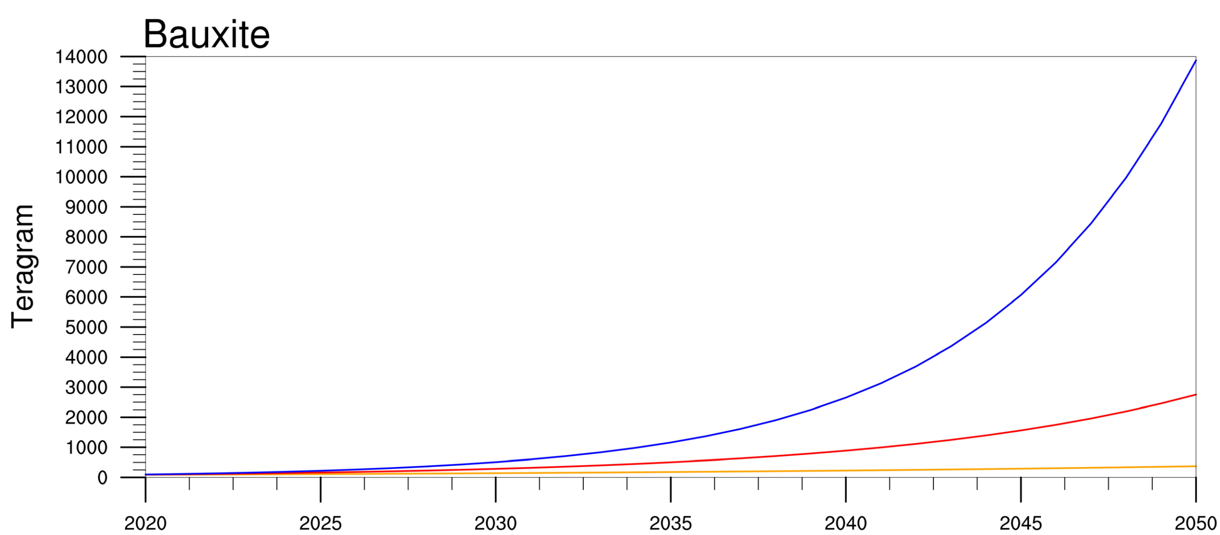
(i)

Figure 4. Global minerals demand as a result of energy transition.

except for Co, Cr, graphite, Mn, and Pt, is estimated to range from 79,000 Tg to 167,000 Tg by 2060 [56]. Therefore, considering mineral production from 2020 to 2050, all mineral demand is projected to increase by between 432% and 14,337%. This finding in the 12% scenario (432% increase in mineral demand) is consistent with Watari *et al.* [57], who stated that the energy transition could potentially result in a 200% - 900% increase in the total material requirement (TMR) flows related to mineral production in the electricity sector and a 350% - 700% increase in the transport sector by 2050.

4.2. The Impacts of the Energy Transition on African Mineral Supplies

Figure 5 shows the growth in yearly mineral production owing to the increasing



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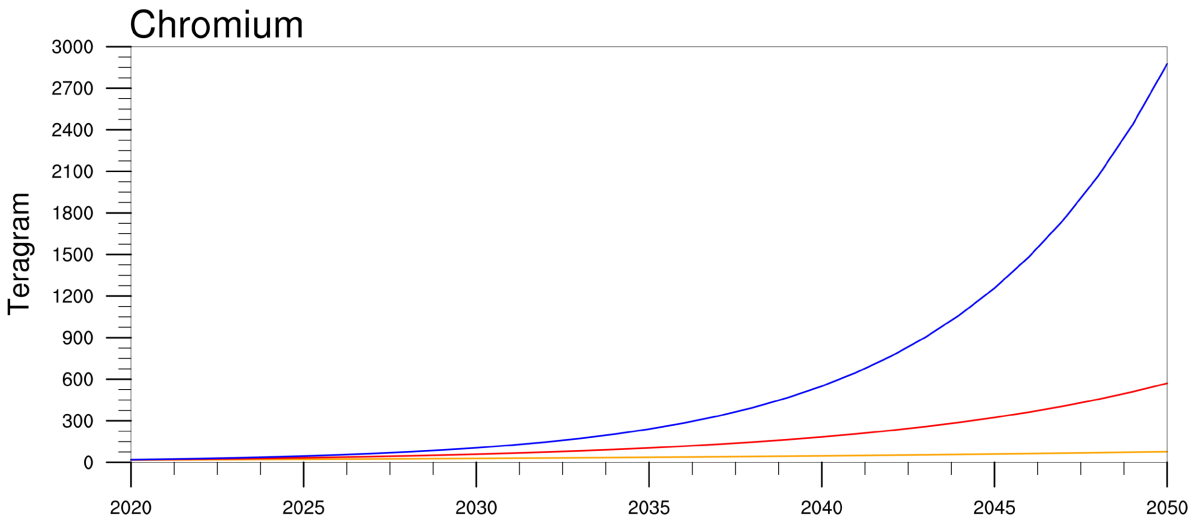
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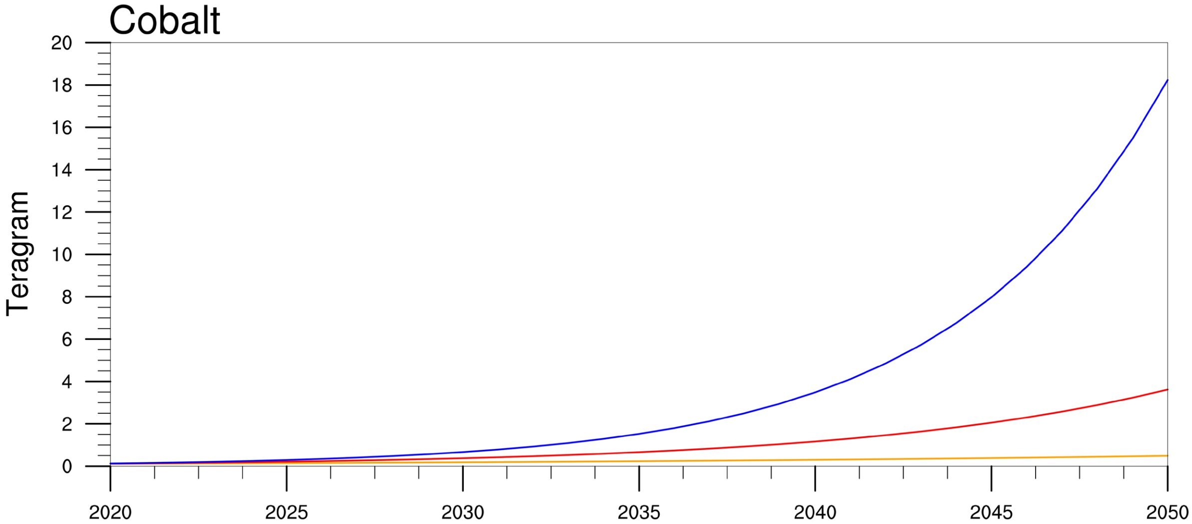
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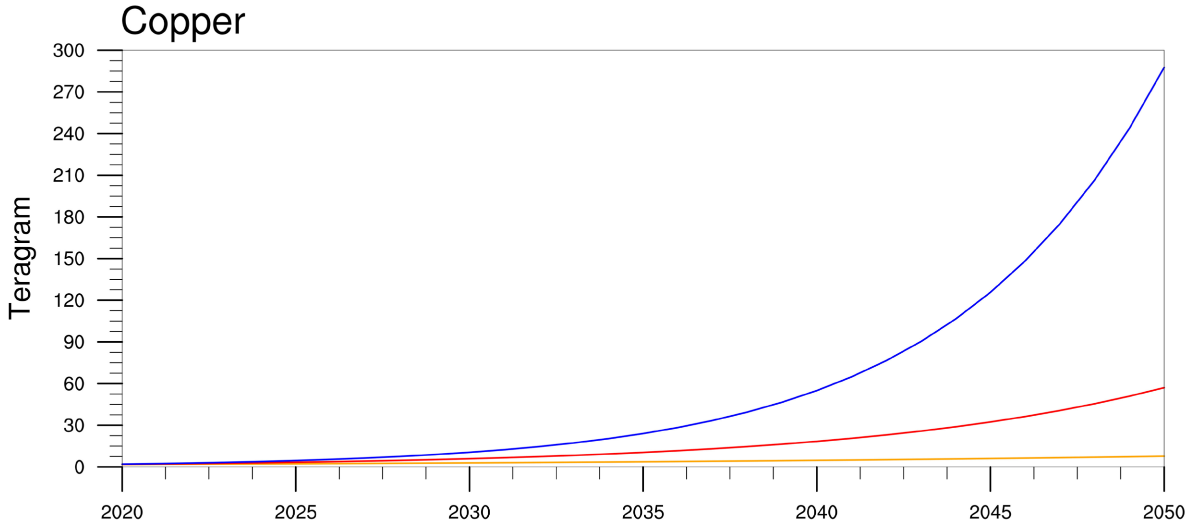
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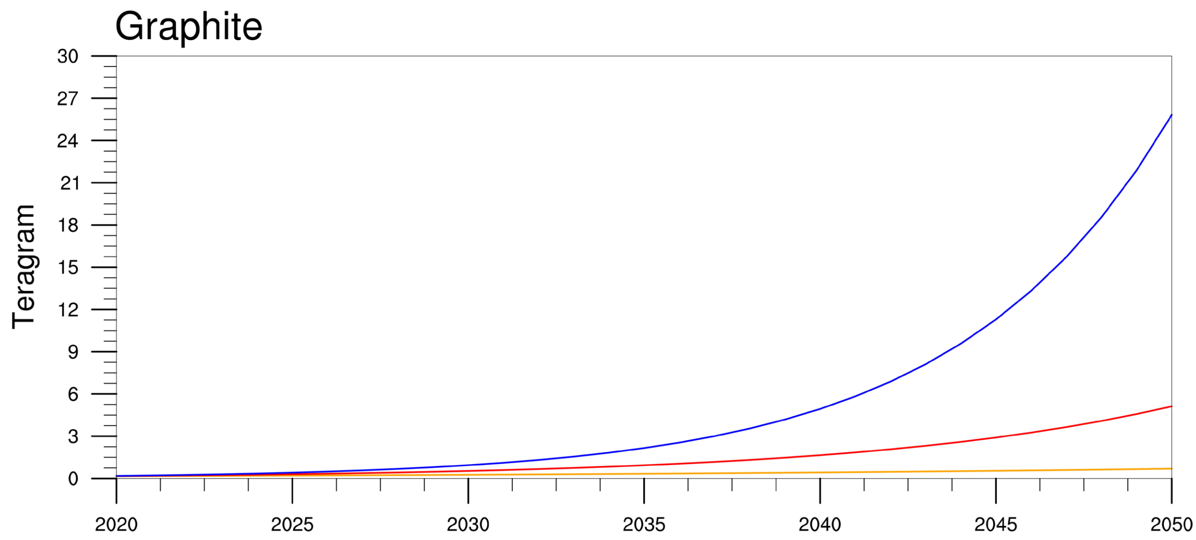
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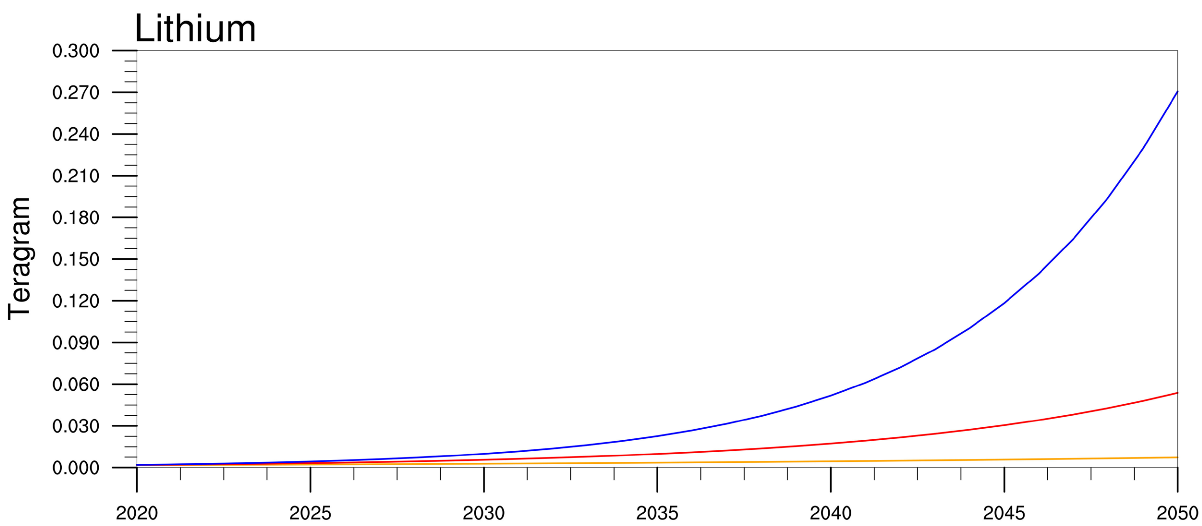
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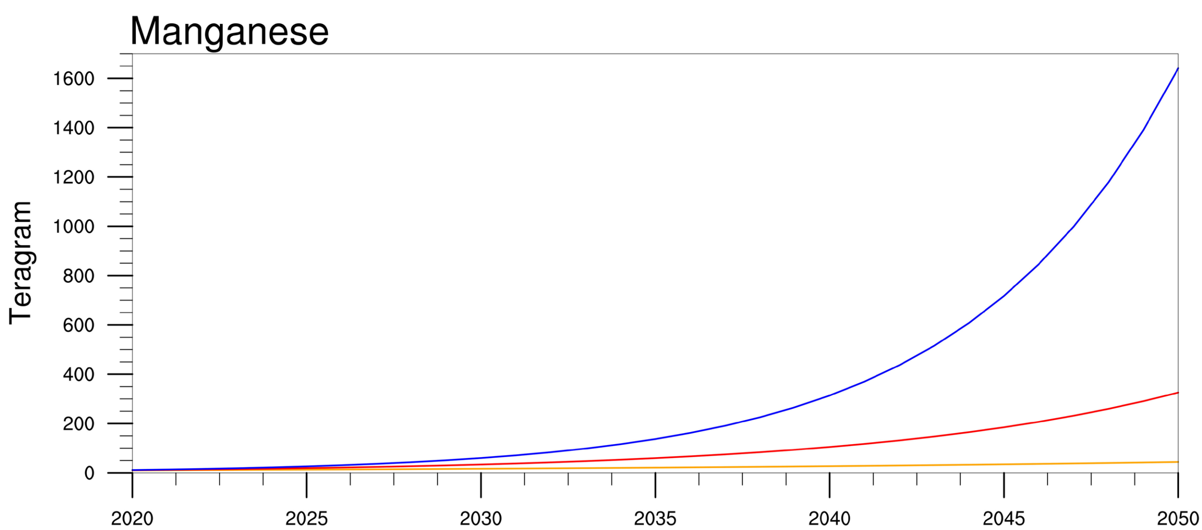
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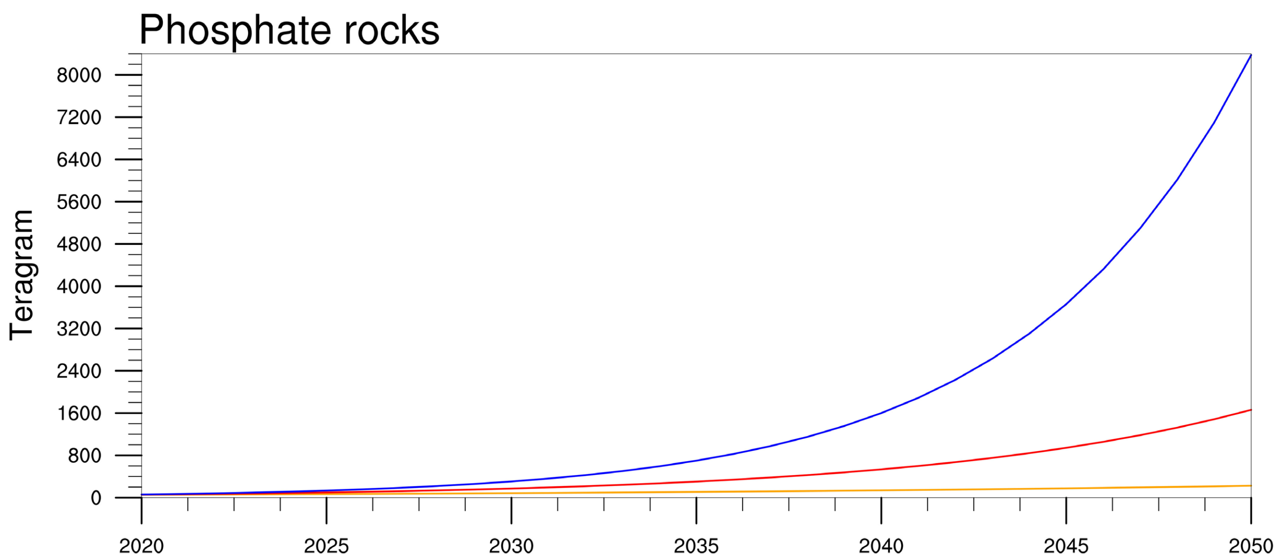

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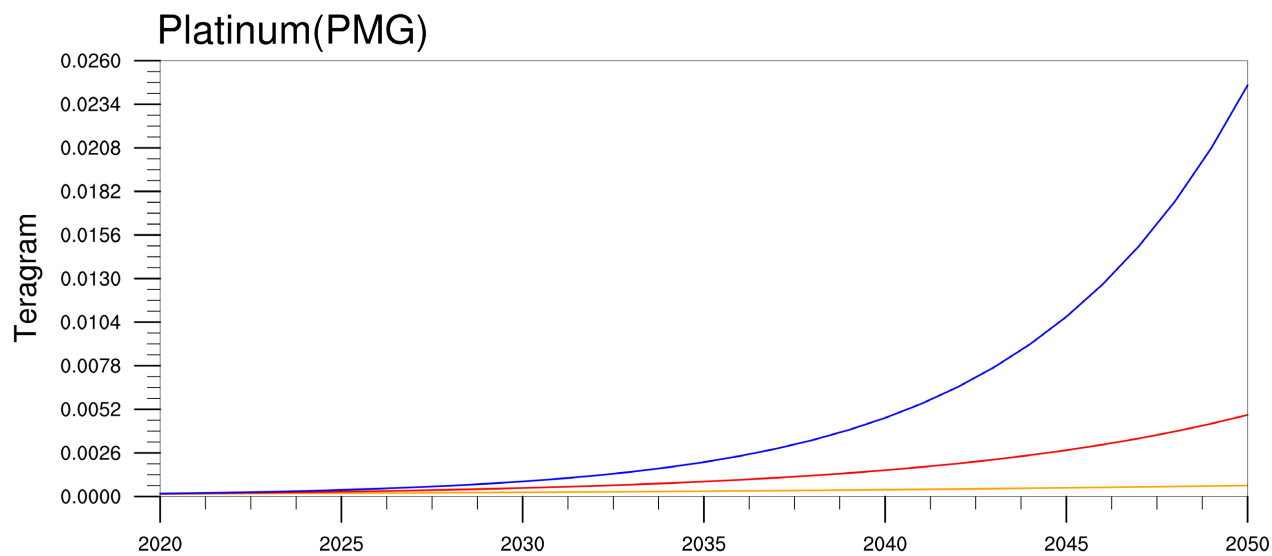


(i)

Figure 5. African mineral supply between 2020 and 2050.

demand for energy capacity systems. The data show an increase in all selected mineral supplies, which is projected to rise annually. However, political instability and collapse can hinder this growth.

Table 4 was analyzed in this study to examine the duration of mineral reserve availability using the 2020 mineral production data for Africa. Furthermore, the cumulative demand for minerals projected for 2050 is compared to determine the percentage of reserve usage by 2050. The results indicate that minerals such as lithium, cobalt, chromium, copper, and bauxite are being overexploited, with depletion rates of 156%, 836%, 2674%, 1245%, and 33579%, respectively. It is projected that additional reserves of these minerals will be needed by 2050, except for platinum, phosphate rocks, and graphite. Phosphate rocks, which are primarily used in agriculture as fertilizers and are aligned with the Sustainable Development Goals (SDGs), will experience the highest demand in scarce regions. In energy technologies, P_2O_5 is required, and Boer *et al.* [58] estimated a global demand of 43 million tons per year. Consequently, our study suggests that the exploitation year projections for all minerals are affected by the indicated scenarios. Valero *et al.* [59] also state that scarce regions will experience the highest demand for phosphate rocks.

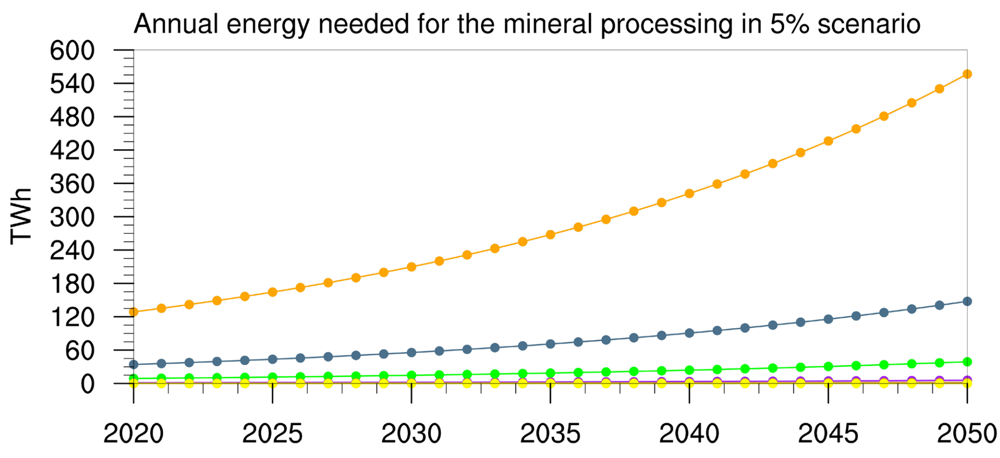
Table 4. African current reserves and production, the number of years that reserve could last under current production, cumulative demand for minerals, and % of the reserve used under the energy transition in the 18% scenario.

Minerals	2020 Reserves[1] (MT)	2021 Annual production (MT)	Lifespan (Years)[2]	Cumulative demand for each mineral (MT)	Mineral reserve by 2050[3] (%)
Lithium	220,000	1,200	184	342,385	156
Platinum	64,200	145	443	34,899	54
Graphite	69,000,000	152,650	452	50,742,569	74
Copper	52,000,000	2,630,000	31	647,195,642	1,245
Manganese	714,000,000	12,140,000	74	3,076,909,823	431
Chromium	200,000,000	18,000,000	12	5,347,719,859	2,674
Phosphate rock	56,780,000,000	73,600,000	772	17,298,881,809	31
Bauxite	7,400,000,000	85,000,000	88	2,484,840,000,000	33,579
Cobalt	3,613,000	124,800	34	30,202,463.29	836

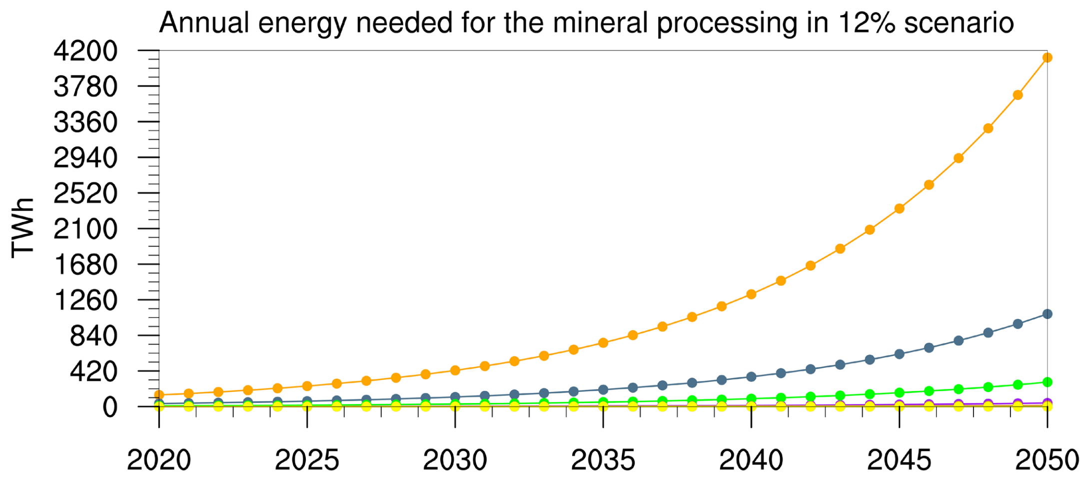
1 (USGS, 2020), 2 the average number of years that a reserve can last under current production, 3% of the reserve used under the energy transition; MT: metric tons [60].

4.3. The Impacts of Mineral Supply on Energy, Water, and Carbon Emissions

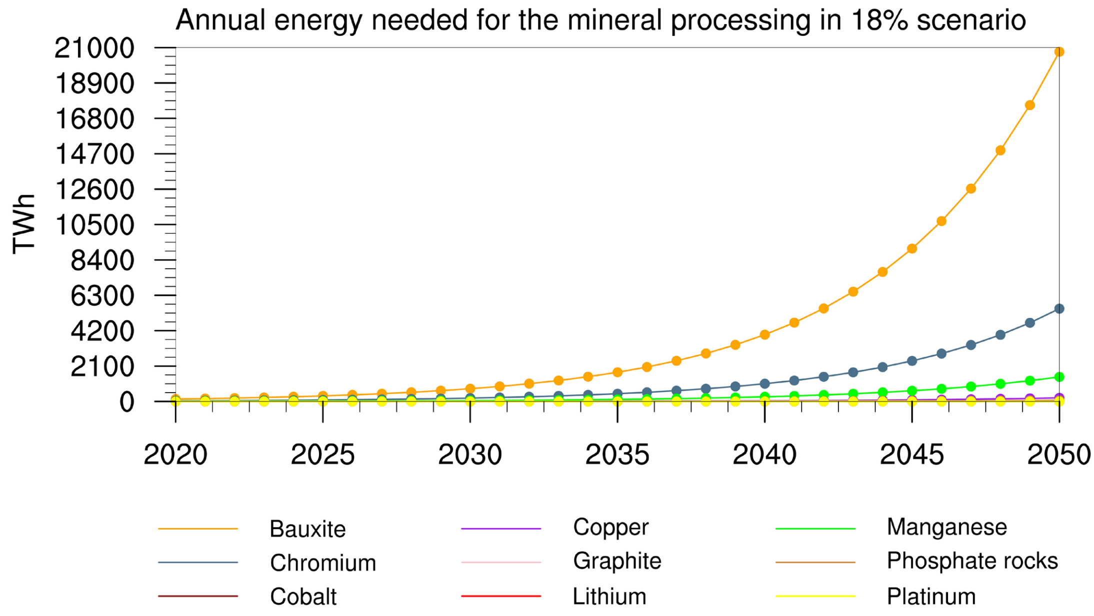
Figure 6 summarizes the cumulative and total energy requirements for the preliminary processing benchmarks, mining plans, and processing costs for bauxite, Pt, phosphate, metallic Mn and Cr, Cu oxide, Co carbonate, and graphite. The



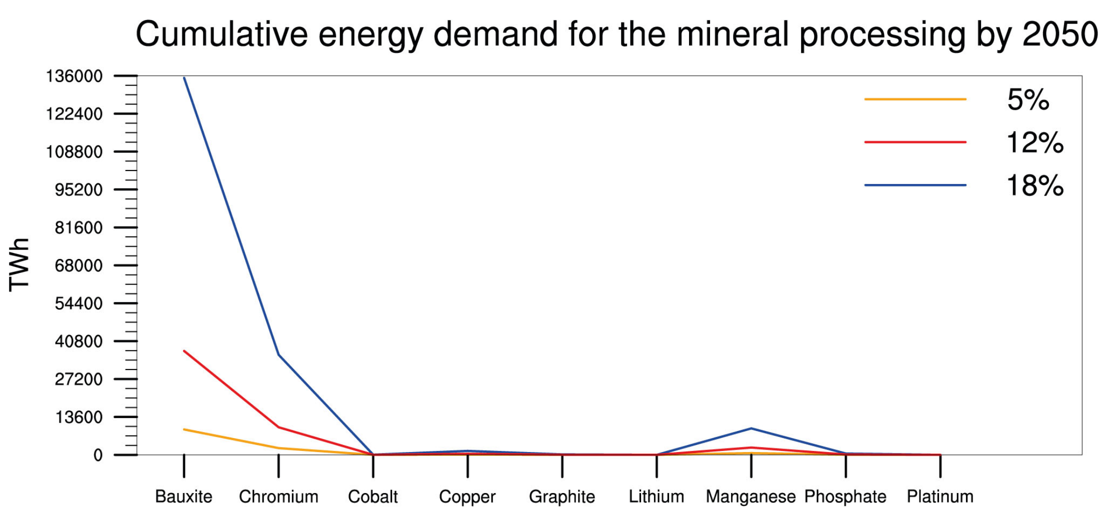
(a)


Annual energy needed for the mineral processing in 12% scenario
TWh
4200
3780
3360
2940
2520
2100
1680
1260
840
420
0
2020
2025
2030
2035
2040
2045
2050

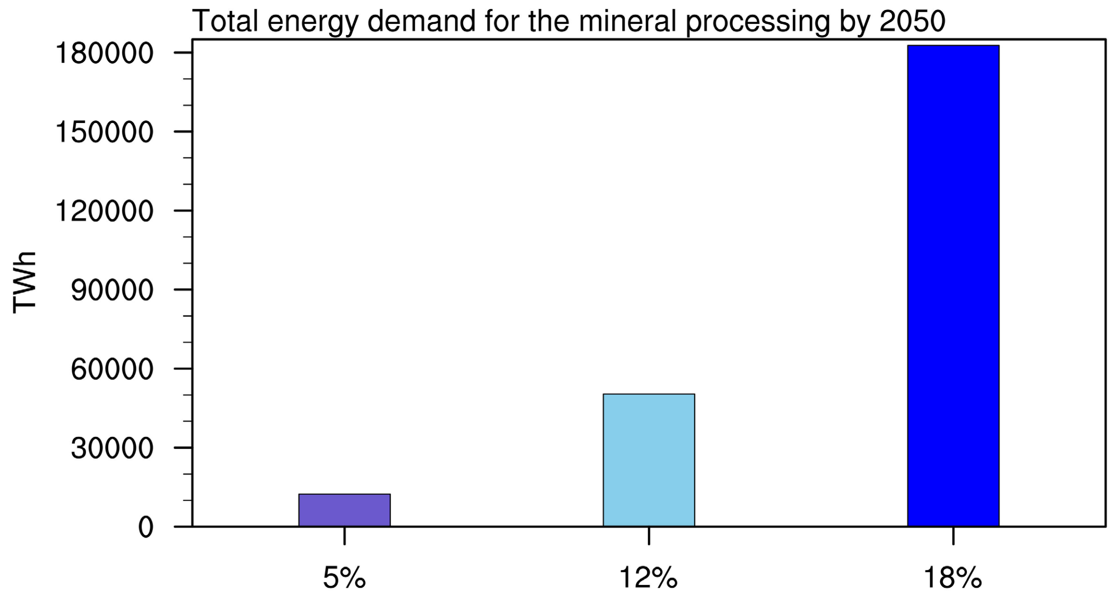
(b)


Annual energy needed for the mineral processing in 18% scenario
TWh
21000
18900
16800
14700
12600
10500
8400
6300
4200
2100
0
2020
2025
2030
2035
2040
2045
2050
Bauxite
Chromium
Cobalt
Copper
Graphite
Lithium
Manganese
Phosphate rocks
Platinum

(c)


Cumulative energy demand for the mineral processing by 2050
TWh
136000
122400
108800
95200
81600
68000
54400
40800
27200
13600
0
5%
12%
18%
Bauxite
Chromium
Cobalt
Copper
Graphite
Lithium
Manganese
Phosphate
Platinum

(d)



(e)

Figure 6. Energy is required for mineral processing. NB: The mining plan and processing costs established the African mining extraction methods [61].

energy required for primary mineral processing is likely to significantly increase in the future.

Table 5 summarizes the annual energy consumption based on the minerals extracted only from the DR Congo, Mozambique, Namibia, the Republic of Guinea, South Africa, Zambia, and Zimbabwe. Due to steady progress in their respective energy sectors, South Africa and Mozambique are prominent electricity producers. In 2020, South Africa had estimated wind and solar capacities of 515 megawatts (MW) and 3061 MW, respectively, whereas in 2019, Mozambique had a hydropower capacity of 2375 MW.

Table 5. Recapitulative of the energy consumed yearly for mineral extraction of the selected African countries for the 2019 and 2021.

Minerals	Energy consumed (TWh)/2019	Energy consumed (TWh)/2021	Countries
Bauxite	4.92	5.1	Guinea
Manganese	44	0.6	South Africa
Phosphates	0.1	0.1	DR Congo
Platinum	0.0000169	0.0000169	Zimbabwe
	0.00000195	0.00000195	South Africa
Cobalt	0.632	0.76	DR Congo
Titanium	12.3	15	South Africa
	8.85	14.5	Mozambique
Copper	1.82	2.1	DR Congo

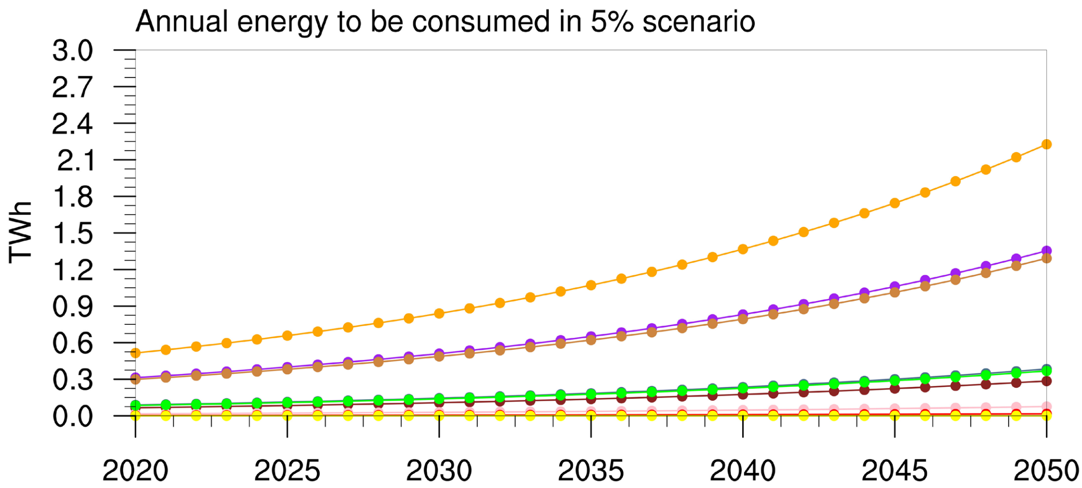
Continued

	1.11	0.5	Zambia
Chromium	0.82	0.9	South Africa
Lithium	0.051	0.04	Namibia
Graphite	0.1	0.03	Mozambique

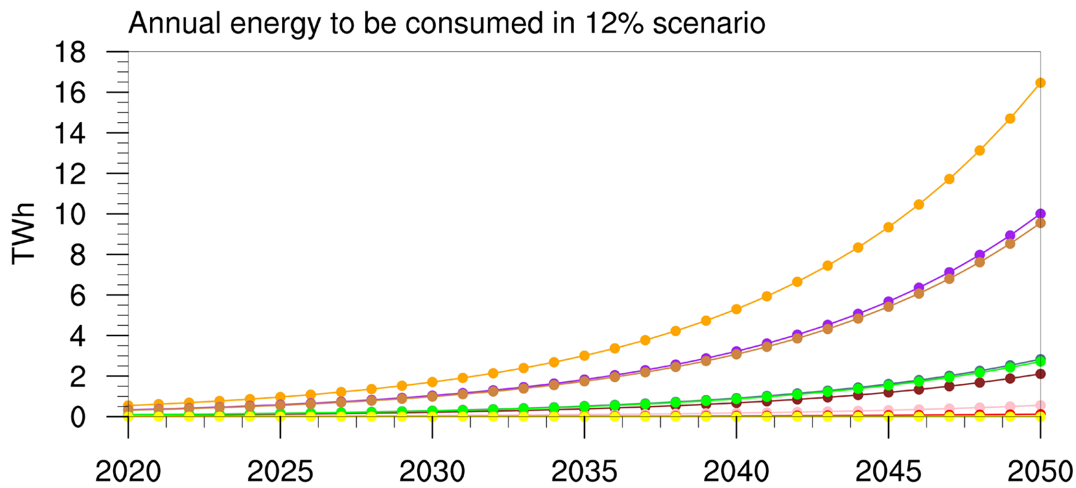
Most of the energy produced by these countries is consumed, leading to considerable GHG emissions [62]. South Africa, with its heavy reliance on coal-fueled power stations, contributes significantly to the country's high GHG emissions, accounting for 93% of electricity generation. Despite efforts to shift towards a low-carbon economy, reducing coal consumption and CO_2 emissions remains a difficult task [61] [63].

According to these findings, each cumulative mineral estimate possesses a considerable amount of energy. Based on the current three-scenario model, the projected total energy required to process these nine minerals is anticipated to reach 12,316 - 182,748 TWh by 2050. This study indicates that there is a substantial increase in yearly energy, water usage, and GHG emissions during mineral extraction (**Figure 7**). Considering the 12% scenario (annual average mineral demand), the estimated total energy required for mineral extraction was 402 TWh by 2050. As of 2020, the current operational African energy capacity has been estimated to be 0.058 TWh, with a total capacity of 0.375 TWh [64]. Additionally, the REMAP IRENA scenario projects an energy demand of 3561 TWh for all sectors in Africa by 2050. These values suggest that the energy used for mineral extraction surpasses current African energy usage. If the energy needed for population growth (207 TWh) is added to the energy required for mineral extraction (402 TWh), the combined total energy will account for 17% of the projected energy demand (3561 TWh) in 2050. Thus, the energy required for mineral processing is approximately 50,365 TWh by 2050 (using the 12% scenario), which is equivalent to 1414% of the energy demand projected by IRENA by 2050. It is important to note that mineral processing is not currently taking place in Africa, although only South Africa and Mozambique produce Al from bauxite.

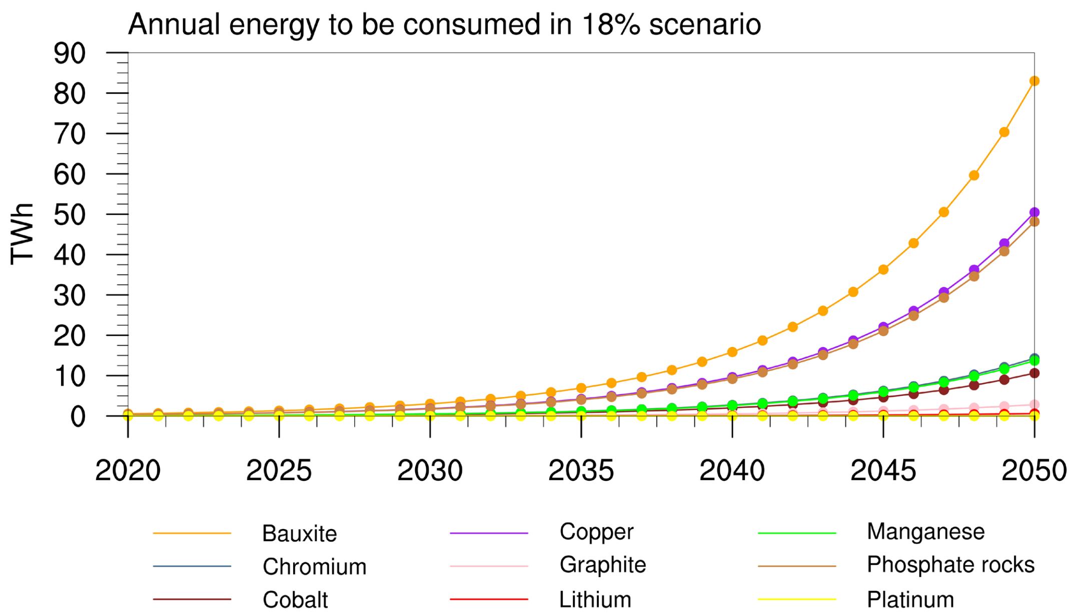
The results also revealed that by 2050, only the mining processes of bauxite, chromium, cobalt, and copper are expected to emit less carbon dioxide than other minerals. However, the water volume necessary for extracting graphite, chromium, and phosphate rocks was not considered in this study. Nevertheless, the data indicate that the estimated range of water volume required is between 15,000 and 223,000 million cubic meters. Compared to previous studies, such as that of Slameršak *et al.* [39], which examined 14 energy pathways of the EROI scenario and reported a global range of 185 - 290 $GtCO_2$ emissions, our estimates were significantly lower. Specifically, our estimates for the ten minerals ranged from 1.34×10^{-3} to 1.96×10^{-2} $GtCO_2$ emissions (1318 to 19,561 $GgCO_2$). While these values may seem small compared to global emissions, they can still be considered significant locally, particularly in areas where mineral extraction is prevalent.


Annual energy to be consumed in 5% scenario
TWh
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
2020
2025
2030
2035
2040
2045
2050

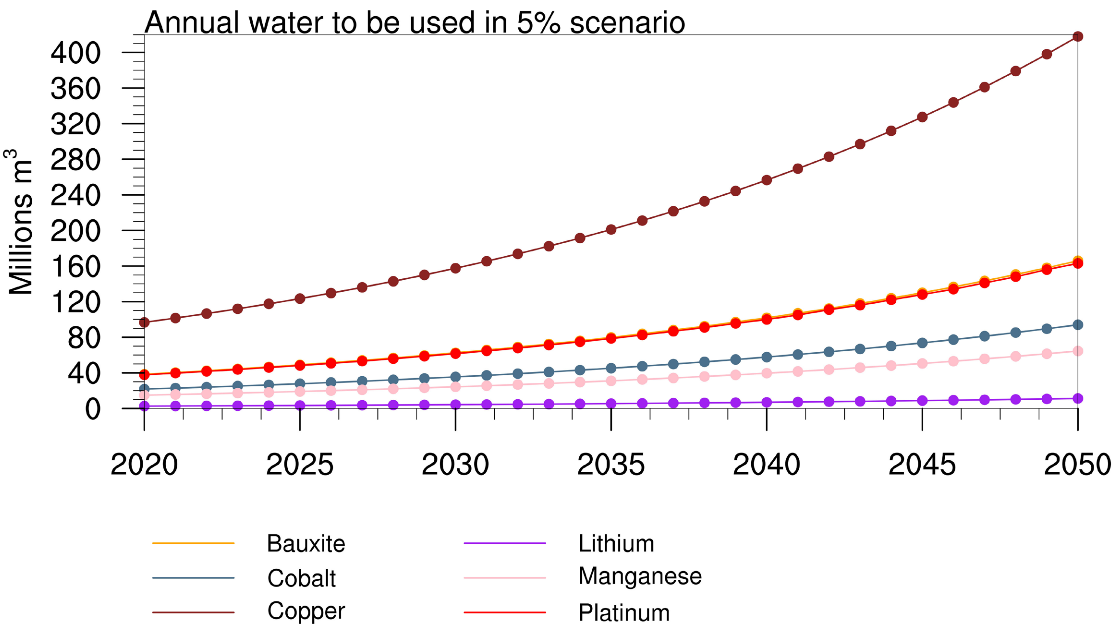
(a)


Annual energy to be consumed in 12% scenario
TWh
18
16
14
12
10
8
6
4
2
0
2020
2025
2030
2035
2040
2045
2050

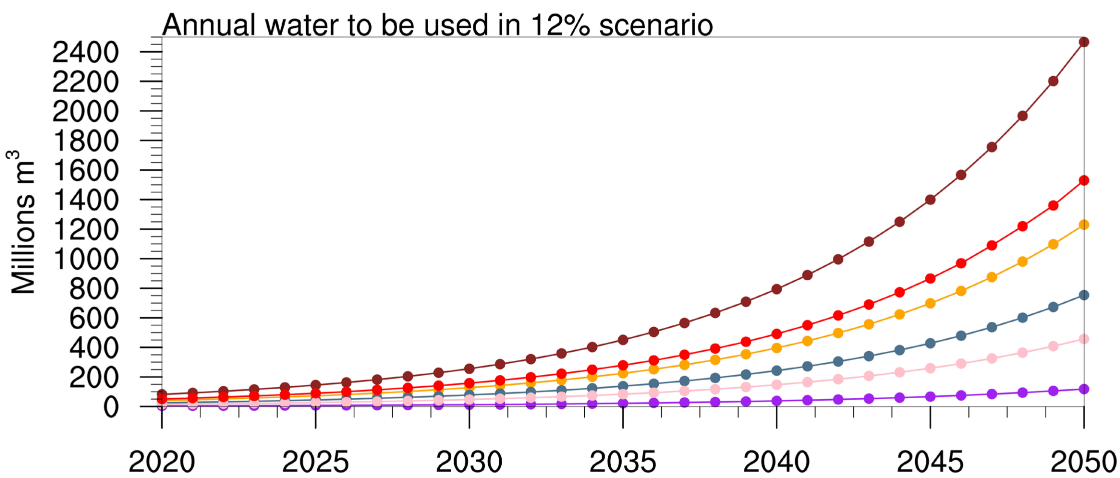
(b)


Annual energy to be consumed in 18% scenario
TWh
90
80
70
60
50
40
30
20
10
0
2020
2025
2030
2035
2040
2045
2050
Bauxite
Copper
Manganese
Chromium
Graphite
Phosphate rocks
Cobalt
Lithium
Platinum

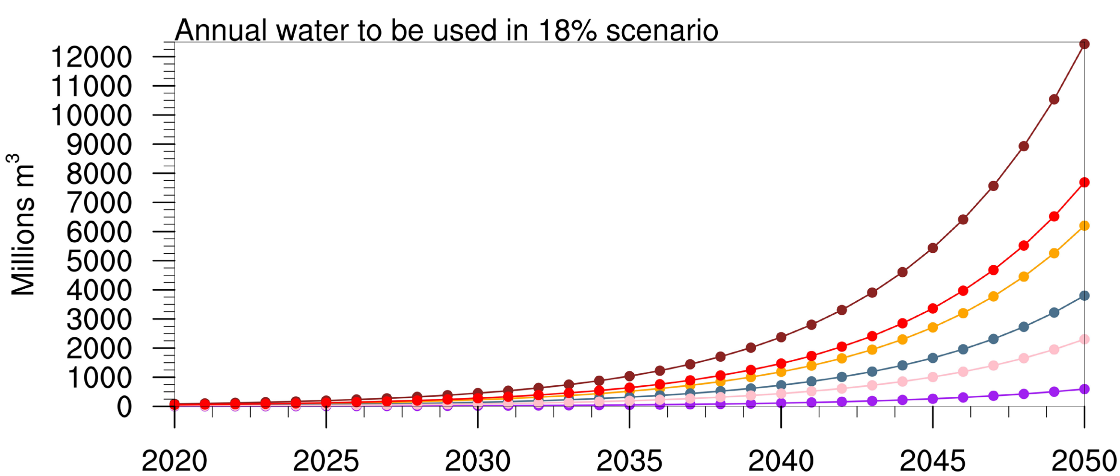
(c)


Annual water to be used in 5% scenario
Millions m^3
0
40
80
120
160
200
240
280
320
360
400
2020
2025
2030
2035
2040
2045
2050
Bauxite
Cobalt
Copper
Lithium
Manganese
Platinum

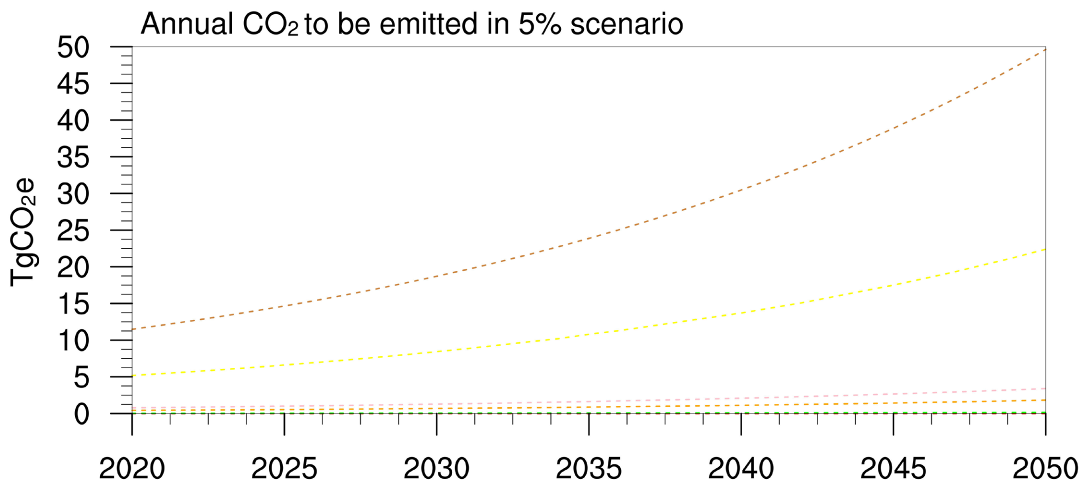
(d)


Annual water to be used in 12% scenario
Millions m^3
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2020
2025
2030
2035
2040
2045
2050

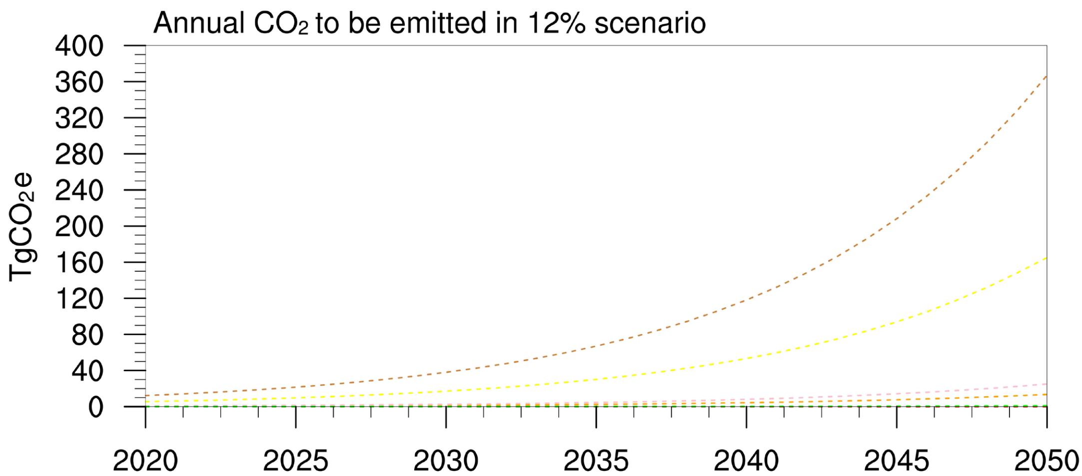
(e)


Annual water to be used in 18% scenario
Millions m^3
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
2020
2025
2030
2035
2040
2045
2050

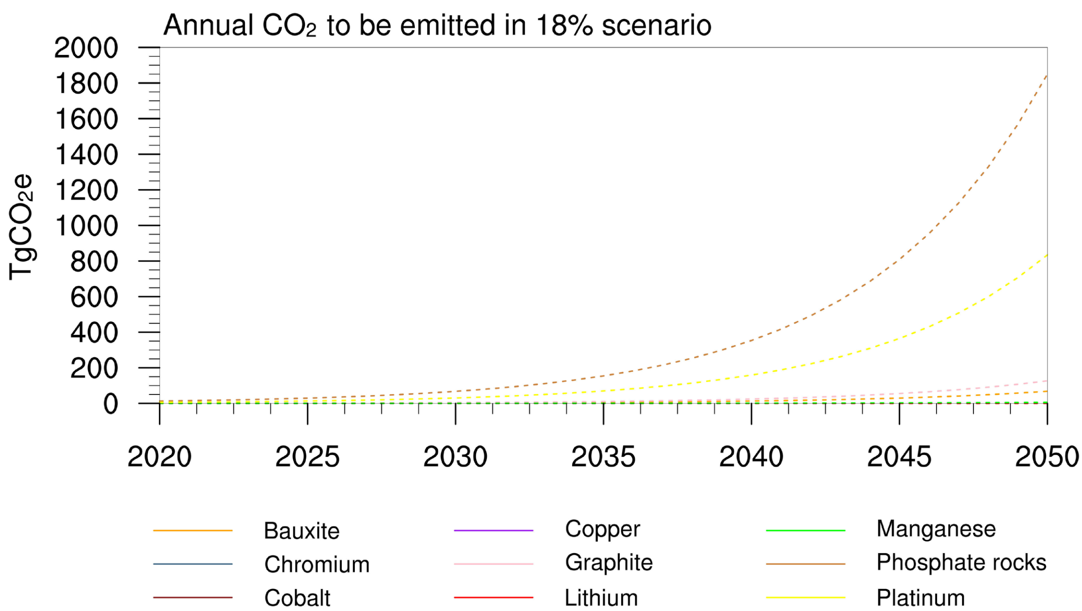
(f)


Annual CO2 to be emitted in 5% scenario
TgCO2e
50
45
40
35
30
25
20
15
10
5
0
2020
2025
2030
2035
2040
2045
2050

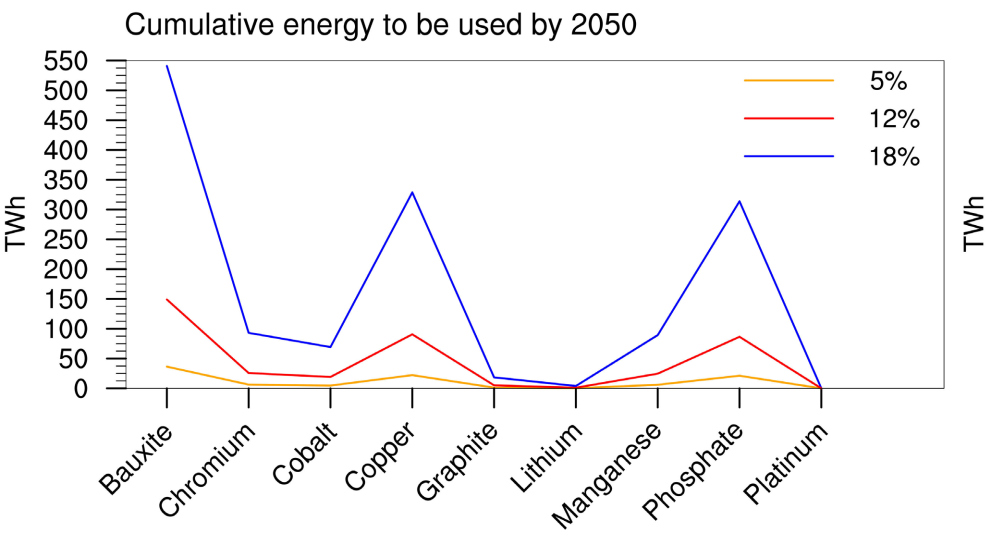
(g)


Annual CO2 to be emitted in 12% scenario
TgCO2e
400
360
320
280
240
200
160
120
80
40
0
2020
2025
2030
2035
2040
2045
2050

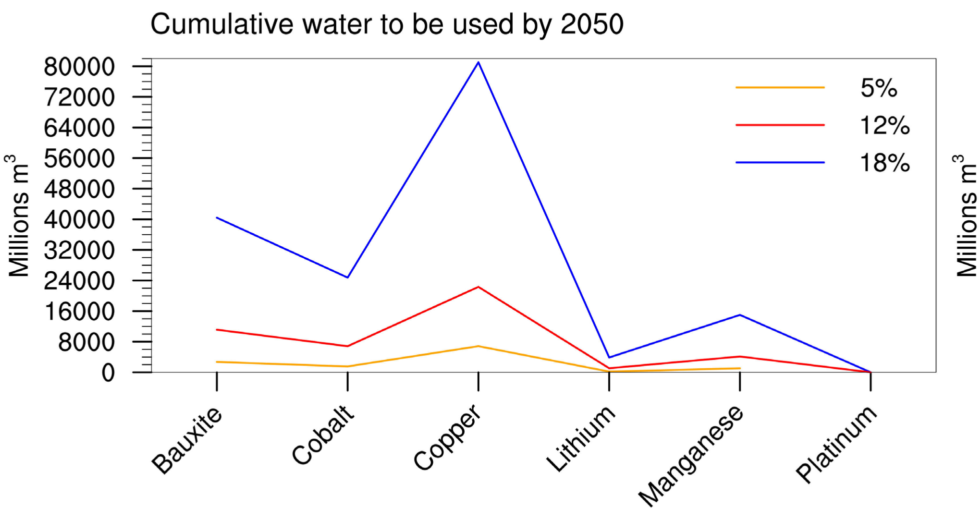
(h)


Annual CO2 to be emitted in 18% scenario
TgCO2e
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2020
2025
2030
2035
2040
2045
2050
Bauxite
Chromium
Cobalt
Copper
Graphite
Lithium
Manganese
Phosphate rocks
Platinum

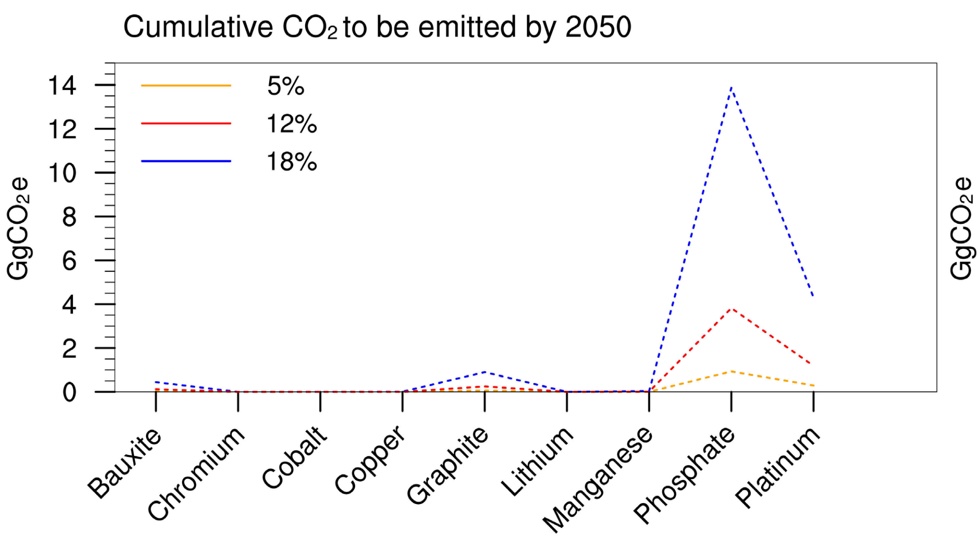
(i)


Cumulative energy to be used by 2050
TWh
550
500
450
400
350
300
250
200
150
100
50
0
5%
12%
18%
TWh
Bauxite
Chromium
Cobalt
Copper
Graphite
Lithium
Manganese
Phosphate
Platinum

(j)


Cumulative water to be used by 2050
Millions m3
80000
72000
64000
56000
48000
40000
32000
24000
16000
8000
0
5%
12%
18%
Millions m3
Bauxite
Cobalt
Copper
Lithium
Manganese
Platinum

(k)


Cumulative CO2 to be emitted by 2050
GgCO2e
14
12
10
8
6
4
2
0
5%
12%
18%
GgCO2e
Bauxite
Chromium
Cobalt
Copper
Graphite
Lithium
Manganese
Phosphate
Platinum

(l)

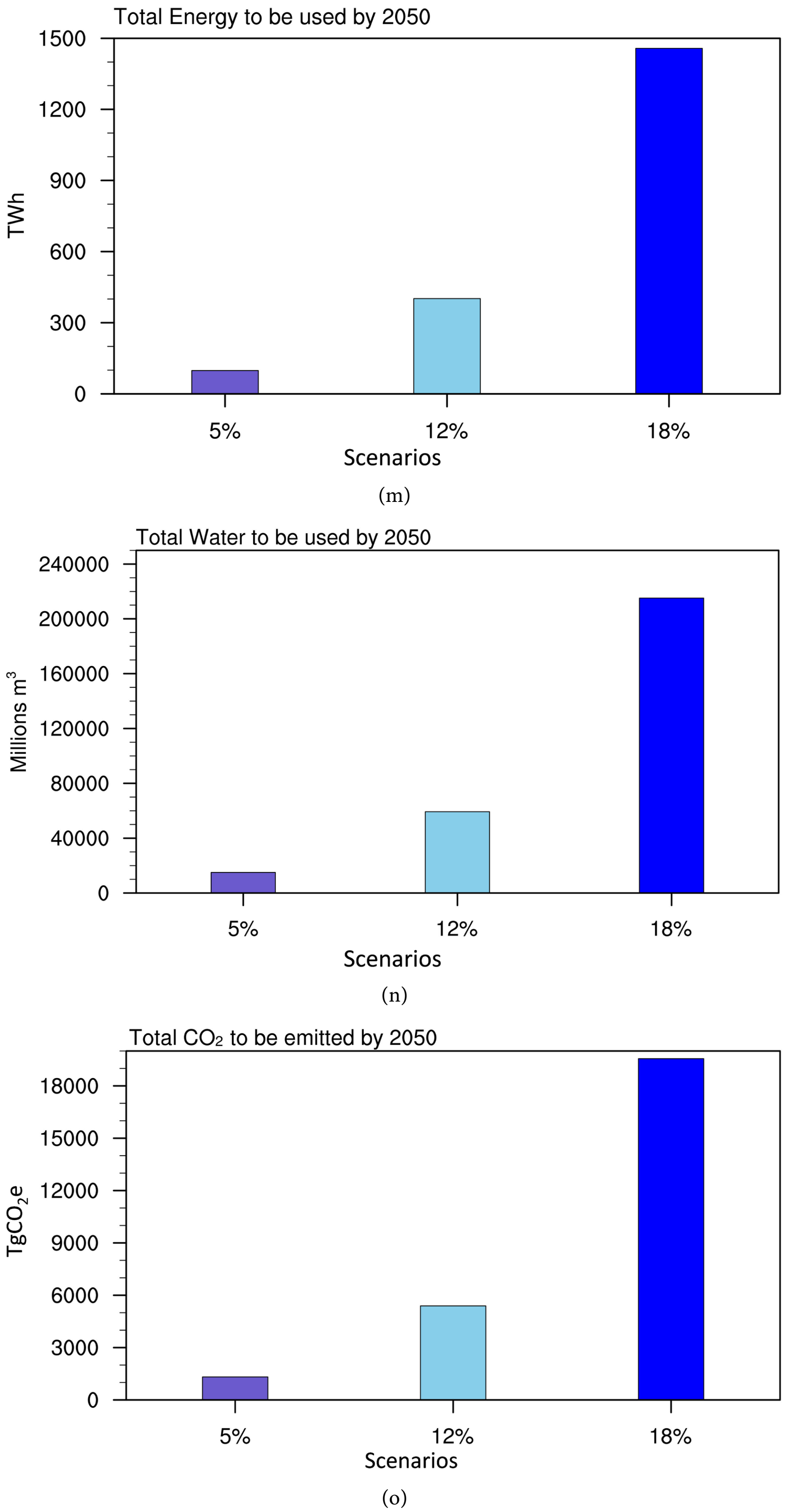


Figure 7. Impacts of the mineral supply on energy, water, and CO_2 emissions in each scenario.

4.4. The Effects of SDGs on Energy Demand in Africa

Figure 8 shows the estimated energy demand based on the population growth rate for Guinea, DR Congo, Mozambique, South Africa, Zambia, and Zimbabwe. For 600 million people needing electricity, the annual demand will increase by 9 TWh/year [44] [65], which suggests that the energy demand increase would be according to the population growth rate of each country. According to the primary goal of SDGs, Africa should grow 50% of its energy demand by 2030 and then make a 100% shift to renewable energy. The energy demand would increase yearly because of technological development and urbanization driven by population growth. According to Statistica, a leading consumer data provider (https://www.statista.com/), Africa generated 4.5 TWh in 2020 from biomass and waste and 0.058 TWh from renewable energy. Considering the estimated energy needed for the population compared to the generated African energy in 2020, the demand will increase to 4445% by 2050.

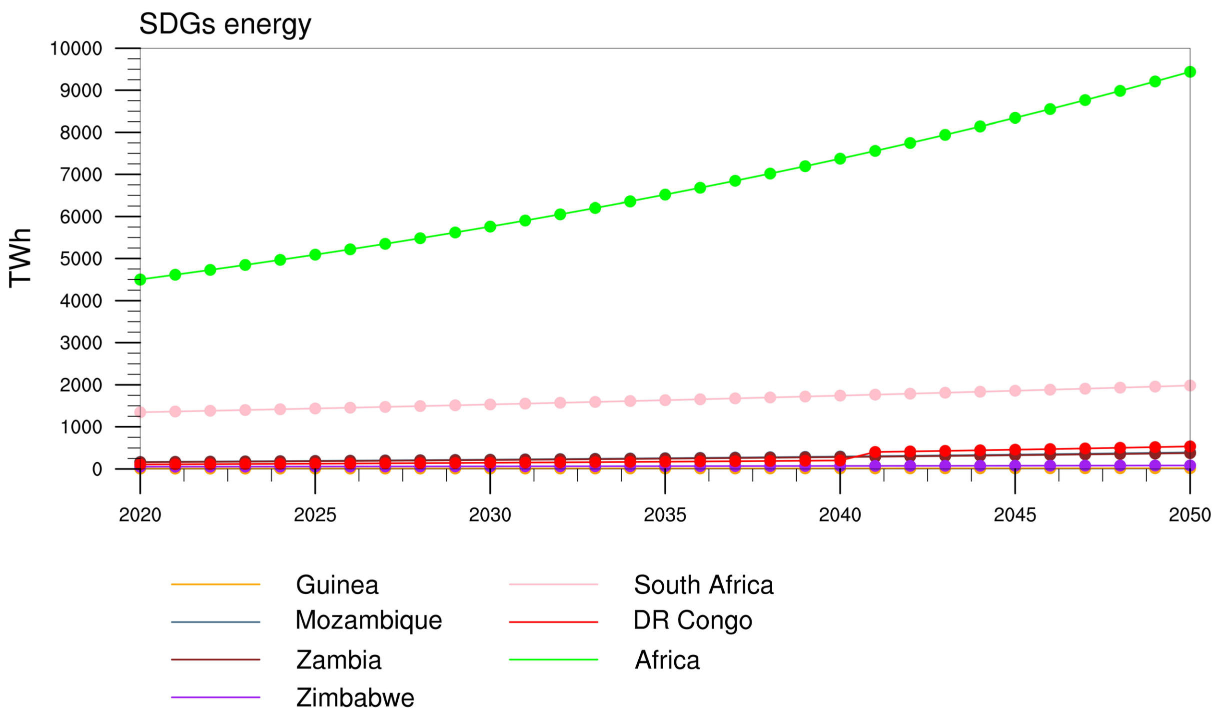


Figure 8. The total annual increase in energy demand for the sustainable development goals achievement.

5. Discussions

The pressing need for a global shift towards renewable energy sources underscores the importance of addressing the mineral demand that supports sustainable energy development. Research indicates that insufficient reserves of critical minerals can impede energy transition [13] [66]. Therefore, it is essential to understand the intricacies of renewable energy adoption and mineral demand to establish effective policies for sustainable energy and transition. Africa presents promising prospects for enhancing renewable energy sources, which can bolster the economy and facilitate the transition to efficient and sustainable energy systems [67]. It is vital to ensure that energy development aligns with environmental sustainability to achieve Sustainable Development Goals (SDGs) and advance energy transitions. The shift towards renewable energy sources in Africa has affected the continent's mineral resources. Africa holds significant reserves of critical minerals that are crucial for renewable energy technologies. However, challenges such as socio-ecological consequences and community displacement arise because of the pursuit of critical minerals for economic competitiveness and environmental sustainability. Moreover, decreasing ore grades and geopolitical barriers threaten the critical mineral supply chain. Research suggests that the growing production of renewable energy is increasing the demand for mineral imports (**Table A5**), indicating a reliance on Africa's mineral resources [68] [69]. Balancing economic demand with environmental concerns and sustainable governance is crucial for achieving sustainable development goals (SDGs) and advancing energy transition. Efforts must be made to assess trade-offs and potential risks associated with mineral extraction, energy consumption, and environmental consequences. Research has examined the carbon footprint of water services in urban systems, drawing attention to the significant energy consumption from fossil fuels [63] [70]. The interdependence of regional trade, energy, water consumption, and carbon emissions underscore the need for an equitable approach to resource management. Challenges, such as climate change and extreme weather events, pose threats to energy systems and demand, highlighting the importance of developing strategies for adaptation and resilience. Balancing energy development with environmental sustainability is critical for achieving the Sustainable Development Goals (SDGs). Industrialized nations prioritize mineral procurement to regulate the market and meet their needs. Strategies for mineral extraction and supply should strive to minimize the long-term environmental consequences. The adoption of sustainable climate policies is recommended for low-income African countries to address the trade-off between energy resources and environmental threats. Addressing environmental challenges is crucial for sustainable development in sub-Saharan Africa. Further research is needed on the nexus approach and role of institutions in facilitating sustainable development. Empirical research on the effectiveness of cross-sectoral approaches and the incorporation of climate risk management into global development policies is essential.

6. Conclusion

This study delves into the complex relationships among minerals, energy, water, and climate across various African countries. As sustainability has emerged as a pressing global concern, Africa faces numerous challenges and opportunities in the energy sector and climate change arena. The findings of this study align with those of previous research, which projects the global mineral demand to range from 79,000 Tg to 167,000 Tg by 2060. The results indicate that minerals such as lithium, cobalt, chromium, copper, and bauxite are being overexploited, with depletion rates of 156, 8360, 26,740, 1245, and 335,790%, respectively. Phosphate rocks, which are widely utilized in agriculture as fertilizers and are aligned with the Sustainable Development Goals (SDGs), will experience the highest demand in regions where resources are scarce. In energy technologies, P_2O_5 is required, and a study has estimated a global demand of 43 million tons per year. As mineral extraction increases and considering the 12% scenario (annual average mineral demand), the estimated total energy required for mineral extraction is 402 TWh by 2050. Although producer countries strive to mine minerals locally, the estimated overall energy needed to process the minerals examined in this study is projected to be 50,365 TWh by 2050 (using the 12% scenario), which is roughly 1414% of the energy demand projected by IRENA for 2050. Despite a scarcity of data on water utilized for Cr, graphite, and phosphate rock extraction, the study found that millions of cubic meters of water will be required, and while the value of GHG emissions seems relatively small compared to global emissions, it is substantially significant locally, especially in areas where mineral extraction is prevalent. Meeting the requirements of SDG7 in Africa and accommodating population growth will likely lead to an increase in energy demand by 9 TWh/year. The lack of empirical research on the efficiency of cross-sectoral strategies and the role of institutions in facilitating nexus approaches in the context of sustainable development in Africa are pressing issues that require immediate attention. Future studies should consider the ethical implications of adaptation measures, and integrate climate risk management into global development policies. Currently, most studies concentrate on regional scales; however, there is an urgent need for research that examines the challenges at various spatial scales and resolutions, while simultaneously addressing the complexities of competition within nexus systems and the uncertainties associated with data and models.

Acknowledgments

We acknowledge all the data centers for providing free access to all datasets used in our study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Studies exploring the resource nexus.

Authors	Key summaries
[71]	This study suggests adopting new economic, technological, and social practices to achieve sustainable consumption and production. This study rethinks its approach by integrating energy and resource systems and considering government regulations and financial incentives. This includes promoting renewable energy technologies and incorporating the resource-energy-water nexus into product design. Moving towards sustainability requires these efforts.
[72]	This study highlights the significance of research in addressing challenges and emphasizes the importance of inclusive development and improved international relations to successfully implement the SDGs. Those using a nexus approach should prioritize academic rigor in their data, evidence, and modeling and disseminate, upscale, and generalize their findings through various fora and scales.
[2]	This study explored the interconnectedness between water, energy, food, greenhouse gases, waste, pollution, and land and the practical implications of addressing these issues for sustainable development. It also discusses the challenges of defining the nexus concept, which has become a popular buzzword. Standardizing the understanding of the nexus, such as quantifying its impact, can help achieve development goals.
[9]	This study examined how Energy Generation technologies will develop in China and what metals are required for their components. It quantifies the demand for 18 metals, compares it with global and Chinese production and reserves, and discusses metal flows and stocks, PV solar technology scenarios, market share, recycling, and IEA scenarios. The study found that there is a significant demand for metals to meet global temperature increase goals and highlights concerns about the availability and production capacity of certain metals. This suggests that future energy models should consider the energy-material nexus for successful implementation.
[12]	This study examined the relationship between Energy Transition Models, energy, water, and CO_2 emissions, and material efficiencies in addressing climate change. The research finds that a higher Energy Generation Transition leads to increased emissions, especially in scenarios with high EGT transitions, such as the IEA SD and GP ADV-REV scenarios. However, the analysis emphasizes the need for regional analysis and evaluation of circular economy business models to fully understand the potential for climate change mitigation in global energy-transition scenarios.
[73]	This study used a quantitative approach to evaluate China's energy transition constraints from a material cycle viewpoint. They calculated the demand for critical Minerals in the solar power sector, revealing a scarcity and supply risk, and found that wind power development requires 10% of China's current reserves of Neodymium and Dysprosium. Thus, China should consider adjusting its renewable energy pathways based on critical mineral endowment and pursuing international trade and material efficiency improvement to support future renewable energy needs.
[74]	This study used a bottom-up energy model to estimate metal requirements for various technologies, including hydrogen and climate policy scenarios, based on assumptions about future metal intensities, recycling rates, and the lifespan of energy technologies. The results show that achieving 100% renewables, coal and nuclear, and gas and renewables pathways has similar warming levels without climate policy, but peak emissions occur within a few decades with a 2˚C policy. This study highlights the critical role of vanadium in all outcomes, and the use of an energy model to study the energy-mineral nexus provides valuable insights for decision-making and policy development.
[75]	This study emphasized the significance of scarce mineral and metal resources in the transition to green energy. It categorizes and ranks 17 critical minerals based on availability, with low indices for key battery minerals, such as cobalt, graphite, and lithium. Enhanced calculation methods were employed to predict demand-supply scenarios for these commodities until 2050, revealing high uncertainty in the forecasted projections.
[76]	This study investigated the effects of renewable energy and globalization on sustainable development in 24 African countries between 1990-2015. This reveals that renewable energy consumption promotes sustainable development, especially in countries that have made moderate progress on the sustainable development agenda. However, these countries must significantly decrease their non-renewable energy consumption. Global collaboration in green policy innovation and research is essential for unlocking SSA's potential of SSA for renewable energy, focusing on making renewables more affordable than fossil-based energy sources to achieve sustainable development goals.

Continued

[3]	This research assessed climate finance strategies for renewable energy development in Africa by examining the challenges and effectiveness of initiatives and financial instruments. It also explores success stories and international climate goal alignment to guide policymakers and stakeholders in refining strategies for a more impactful renewable energy transition in Africa.
[72]	Tensions rise along the Nile River as Ethiopia constructs the Grand Ethiopian Renaissance Dam. Egypt is concerned about water shortages and is considering sanctions, while Ethiopia is seeking to increase its electricity supply. The United Nations Security Council recommends discussions with the African Union. This article explores the connection between water and energy in international relations, offering constructive perspectives to address energy systems, water management, and food security in future negotiations and institution-building initiatives.
[77]	Recycling is debated for environmental and resource conservation reasons; however, its effectiveness is questionable. Mining is facing declining ore grades, while recycling is hindered by material dispersion into products or waste, increasing the effort required. Determining the optimal recycling rate by optimizing the overall recycling system is crucial. Establishing political goals for a Circular Economy is necessary before this can be achieved.

Table A2. Impact linking to mineral production technologies.

Minerals	The energy required for production	Extraction methods	Associated impacts	References
Bauxite	60 kWh/t	Open-pit/Electrowinning	Loss of habitat and food for local wildlife	[40]
Platinum	130 kWh/t rock	Open-pit/Underground mining/Electrowinning	High waste rock and tailings generated (98% of the ore becoming tailings), High electricity consumption (average 175 GJ/kg PGM), water usage (average 400 m^3/kg PGM), and CO_2 emissions (average 40 t CO_2e/kg PGM.)	[40]
Pure Titanium sponge	15,000 kWh/t Products	Vacuum distillation	Removal of vegetation cover and topsoil, massive amounts of water	[51]
Phosphate	50 kWh/t Products	Mining with draglines (waste to ore ratio 1:1) and slurry pumping to the beneficiation plant	Polluted air, contaminated water, and destruction of valuable wildlife habitat	[40]
Manganese metal from reduced or sintered ore	80 kWh/t manganese ore	Open-pit/Electrolysis of aqueous solution (Nelspruit process)	Can cause toxicity and deficiency symptoms in plants and humans	[40]
Chromite ore	48 kWh/t	Open-pit/Electrolysis	Health effects negatively affect plant metabolic activities, hampering crop growth and yield and reducing vegetable and grain quality.	[40]
Copper oxide ores and sulfide ores	1400 kWh/t Cu	Open-pit/Electrowinning	It affects drinking water aquifers, contaminates farmland, contaminates and loss of fish, wildlife, and their habitat, and risks to public health.	[40]
Cobalt carbonate from primary sources	6322 kWh/t	Open-pit/Electrowinning	Cause vision problems, vomiting and nausea, heart problems, and thyroid damage.	[42]
Natural graphite	1000 kWh/t	Surface/underground mining	Loss of habitat and pollution, contamination of surface and groundwater	[78]
Lithium	32,000 kWh/t	Electrolysis	Water depletion, ground destabilization, biodiversity loss, increased salinity of rivers, contaminated soil, and toxic waste	[78]

Table A3. The annual projection of mineral demand in each scenario by 2050 (in metric tons).

Minerals	2020 Global mineral production (USGS 2020)	5%	12%	18%
Graphite	1,155,000	4,991,843	36,910,624	1.86E+08
Copper	2.10E+07	9.1E+07	6.71E+08	3.38E+09
Manganese	2.00E+07	8.6E+07	6.38E+08	3.21E+09
Chromium	4.62E+07	2E+08	1.48E+09	7.44E+09
Bauxite	3.89E+08	1.68E+9	1.24E+10	6,26E+10
Cobalt	147,000	635,326	4,697,716	23,684,829
Lithium	80,850	349,429	2,583,744	13,026,656
Platinum	189	953	7047	35,527
Phosphate rocks	2.52E+08	4,991,843	37E+6	1.86E+08

Table A4. The annual projection of mineral demand found in studies.

Minerals	Previous study's estimation (MT)	Periods	Authors
Bauxite	140E+6 - 215E+6	2010-2050	[79]
	650E+3 - 9550E+3	2012-2050	[80]
	5.58E+06	2019-2050	[75]
	29E+6 - 100E+6	2018-2050	[69]
Chromium	3.66E+05	2019-2050	[75]
Cobalt	1300E+3 - 2200E+3	2015-2060	[81]
Copper	285E+3 - 1540E+3	2012-2050	[80]
Graphite	4.59E+06	2015-2050	[75]
Lithium	2.28E+6 - 16.74E+6	2015-2100	[82]
	242E+3 - 2079E+3	2020-2050	[83]
	1719E+3 - 2031E+3	2000-2100	[84]
Manganese	6.94E+05	2019-2050	[75]
Phosphate rocks	28E+6 - 50E+6	2011-2118	[85]
Platinum	6000 - 47,000	2007-2050	[86]
	109 - 2541	2021-2050	[87]

Table A5. Different technologies in which the minerals extracted are used in the energy transition [69].

Minerals	Bauxite (Aluminum)	Chromium	Cobalt	Copper	Graphite	Lithium	Manganese	Phosphate rock	Platinum
Technologies	Transportation	Solar Photovoltaic (PV) Panels	Lithium-ion Batteries	Power Generation	Lithium-ion Batteries	Lithium-ion Batteries	Lithium-ion Batteries	Lithium Iron Phosphate ($LiFePO_4$) Batteries	Fuel Cells
	Packaging	Wind Turbines	Renewable Energy Storage	Wind Energy	Redox Flow Batteries	Electric Vehicles (EVs)	Renewable Energy Systems	Advanced Lead-Acid Batteries	Hydrogen Production
	Construction	Energy Storage:	Solar Photovoltaics	Electrical Grids	Fuel Cells	Energy Storage Systems (ESS)	Hydrogen Production	Sodium-Ion Batteries	Renewable Energy Storage

Continued

Electrical Industry	Fuel Cells	Hydrogen Fuel Cells	Energy Storage	Solar Photovoltaic (PV) Cells	Portable Electronics	Carbon Capture and Storage (CCS)	Phosphoric Acid Fuel Cells (PAFCs)	Hydrogen Fueling Station
Consumer Electronics:	Hydrogen Production:	Wind Turbines	Electric Vehicles (EVs)	Nuclear Reactors	Renewable Energy Integration	Nuclear Power Generation	Phosphate Rock for Fertilizer Production	Offshore Wind Power
Renewable Energy:	Sustainable Infrastructure:	Electric Aerospace	Geothermal Systems	Thermally Conductive Materials	Smart Grids			Solar Energy
Marine Industry:			Hydro Power	Water Purification	Renewable Power Plants			
Sports Equipment				Carbon Capture and Storage (CCS)				
Medical Devices:				Coating and Lubrication				