MINING AND THE CIRCULAR ECONOMY

South Africa's resource availability as a driver for transitioning to a Circular Economy

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EXECUTIVE SUMMARY

The objectives of this study were to determine whether resource scarcity is a potential driver (or not) for South Africa to transition to a circular economy; and to explore the circular economy opportunities in the mining sector. The project objectives were achieved by answering five research questions relating to (i) the economically viable minerals remaining in South Africa, (ii) determination of South Africa's critical / strategic minerals, (iii) historical mineral demand trends, (iv) resource scarcity as a driver for South Africa to transition to a circular economy, and (v) the potential circular economy opportunities for the South African mining sector.

The results obtained from calculating the remaining years of economically viable minerals in South Africa indicated that some minerals have less than 50 years of economically viable mining remaining, assuming no new major reserves are found, and demand, supply and hence economic value remains unchanged. This raises concerns regarding mineral depletion and the impacts thereof on the South African economy. The calculated years to depletion are indicative and based on current knowledge of parameters such as current reserves, current production rates, and demand and supply.

Analysis of the historical mineral demand trends showed that coal had the highest returns from local sales, which may have been due to the country's continued reliance on coal for electricity generation. In 2019, platinum group metal (PGM) export sales increased the most, which is likely due to increasing developments in 4IR and decarbonisation technologies that tend to increase the demand for critical minerals.

Eighteen minerals were identified as critical / strategic in South Africa due to their economic importance and supply risk. The critical minerals in South Africa include aggregate, bauxite, chromite, cobalt, copper, gold, graphite, iron, limestone, lithium, manganese, nickel, phosphorous, PGMs, rare earth elements (REEs), silver, titanium and vanadium.

The just-transition to cleaner and greener energy necessitates investigations into alternative uses for coal so that the economic benefit that South Africa currently gains from coal sales is not completely lost. Additionally, to avoid locking South Africa into an export model, local beneficiation, and manufacturing of PGM (amongst other minerals) becomes increasingly important as the demand for critical minerals increases.

Based on the findings, it was agreed that resource scarcity may in fact be a driver for South Africa to transition to a circular economy. However, other factors can also be considered as drivers like job creation, socio-economic development, climate commitments, and business objectives, amongst others. It can therefore be argued that all mineral commodities are scarce and should be used sparingly and in a sustainable and responsible manner, for the benefit of present and future generations. Urgent priority should be directed to those commodities that may potentially be depleted within the next 50 years of extraction – cobalt, gold, iron ore, lead and manganese – by investigating or identifying possible circular economy opportunities for these commodities. These minerals, however, are mostly exported, suggesting that South Africa may have little control over their downstream circularity. Therefore, it is recommended that local beneficiation and local manufacturing should be prioritised so that South Africa may realise the benefits of its own resources. Additionally, the idea of resource leasing as opposed to resource sales to trading partners may be further explored as a potential means to encourage responsible and sustainable resource use.

Following an in-depth study that involved collating secondary data through literature review, survey questionnaires, and stakeholder engagements, the most implementable circular economy opportunities in the mining sector are aligned with the "*keep materials in use*" principle. These include reducing, reusing and recycling of materials. Although some of the opportunities mentioned within this category are not new concepts, challenges still remain when it comes to implementation of these initiatives. The challenges are mainly operational and financial, suggesting that research, development and innovation are key focus areas to addressing these issues. In terms of financial constraints to implementation, the cost versus long-term benefit of these interventions needs to be studied and realised.

Even though some mining companies adopt circular economy principles, the interventions need to be scaled up to make a meaningful impact on South African business, society, environment, and the economy. A considerable number of circular interventions have been identified for the mining sector, some of these may require time to implement, making them more suitable for medium- to longer-term implementation.

CONTENTS

ACRONYMS

4IR	Fourth Industrial Revolution
AAGR	Average Annual Growth Rate
CAGR	Compound Annual Growth Rate
CE	Circular Economy
CLAS	Cement, Lime, Aggregates and Sand
COVID-19	Coronavirus Disease
CRM	Critical Raw Materials
CSIR	Council for Scientific and Industrial Research
DMRE	Department of Mineral Resources and Energy
ECSA	Engineering Council of South Africa
E-mobility	Electric Mobility
EU	European Union
EV	Electric Vehicle
E-waste	Electronic Waste
FCEV	Fuel Cell Electric Vehicles
GDP	Gross Domestic Product
GHG	Greenhouse Gas
LED	Light-emitting Diode
MCSA	Minerals Council South Africa
MMS	Mining and Metals Sector
MPRDA	Mineral and Petroleum Resources Development Act
MQA	Mining Qualifications Authority
OECD	Organisation for Economic Co-operation and Development
PGM	Platinum Group Metals
PV	Photovoltaic
PwC	Pricewaterhouse Coopers
RDI	Research, Development and Innovation
REE	Rare Earth Elements
SA	South Africa
SACNASP	South African Council for Natural and Scientific Professions
SADC	Southern African Development Community
SAGC	South African Geomatics Council
SAMREC code	South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SDG	Sustainable Development Goal
TSF	Tailings Storage Facility
UAV	Unmanned Aerial Vehicle
USGS	United States Geological Society
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background

The Ellen MacArthur Foundation (EMF) defines a circular economy as a "*systemic approach to economic development designed to benefit businesses, society, and the environment*" (EMF, 2017).

Our current linear economy is essentially a 'take-make-waste' model. This means that resources are extracted from the natural environment and used to make products, which are often used for only a short period of time, before being discarded back into the environment. This process results in huge amounts of wastage of materials, water and energy (Nahman, *et al.*, 2021).

In contrast to the linear 'take-make-dispose' economic model, a circular economy (Figure 1) entails:

> "*keeping materials and products in circulation for as long as possible through practices such as reuse and repurposing of products, sharing of underused assets, repairing, recycling and remanufacturing.*"
> (Schroder, 2020)

A circular economy also aims to gradually decouple growth from the consumption of finite resources (Nahman, *et al.*, 2021).

Early approaches to the circular economy placed mining outside of the concept, however, recent studies show that the circular economy has a lot to offer the mining sector through sustainable resource use (Figure 2).

The circular economy is an evolving concept that has gained traction over the past four to five years with business and government leaders. It has also appeared in a number of new South African policies, including the White Paper on Science Technology and Innovation (DSI, 2019), the 3rd National Waste Management Strategy (DEFF, 2021) and in the new Department of Science and Innovation Decadal Plan (2021-2031).

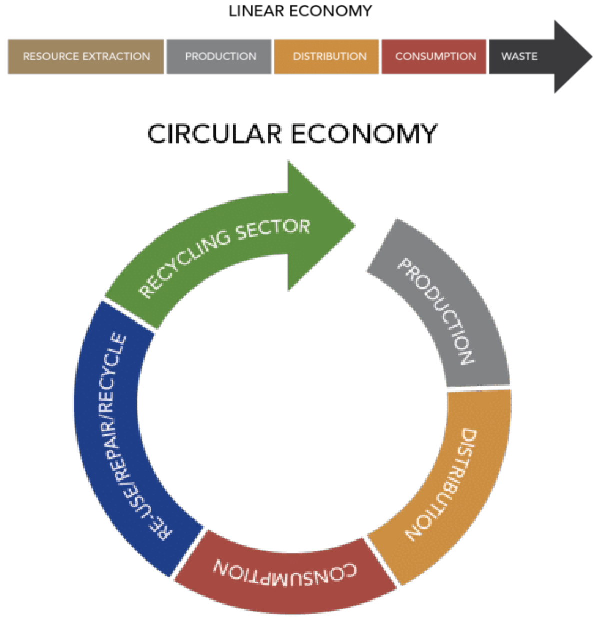

Figure 1. Linear versus circular economy (WEF, 2016)

This study relates to the circular economy in the context of the South African mining sector and is part of a broader CSIR cross-unit project titled,

> "*Identifying opportunities for a more circular South African economy – A resource perspective.*"

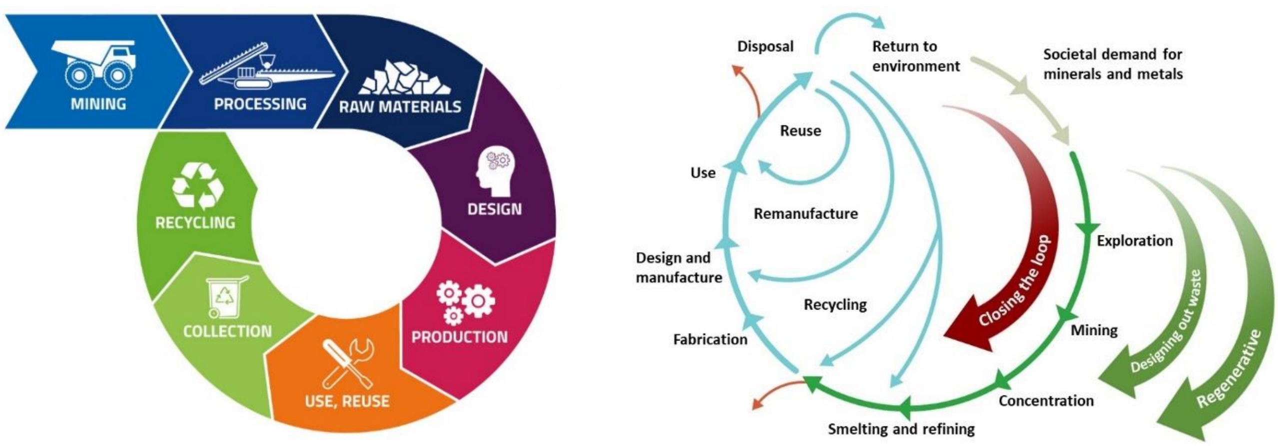

Figure 2. Integrating the main life cycle stages for minerals and metals into the circular economy (adapted from EIT (2018); ICMM (2016))

1.2 Objectives

The objectives of this study were:

- To determine whether South Africa's resource availability is a potential driver (or not) to transition to a circular economy; and
- To explore the circular economy opportunities in the South African mining sector.

The following research questions were addressed:

1) How many years of economically viable minerals and metals does South Africa have?
2) What are South Africa's critical / strategic minerals?
3) What are the historical demand trends on South Africa's mineral resources?
4) Based on 1, 2 and 3 above, is resource scarcity the / a driver for South Africa to transition to a more circular economy?
5) What are the circular economy opportunities for the mining sector and their appropriateness (and challenges) for South Africa?

1.3 Methodology

The methodology employed to understand South Africa's resource availability, constraints, critical raw materials, and drivers of the transition to a circular economy included an initial desktop study aimed at understanding the relevance of the circular economy to the mining sector. This culminated in the publication of a short, introductory briefing note entitled "*Placing the South African mining sector in the context of a circular economy transition*" (Khan, *et al.,* 2021). The initial concepts of the research that were documented in the briefing note were presented at the CSIR Circular Economy project launch held in November 2021 and published by the CSIR in a book entitled, "*The circular economy as development opportunity*" (Godfrey, 2021). This was followed by a more in-depth study which involved collating secondary data through literature review, gathering primary data through stakeholder engagements, survey questionnaires, and stakeholder workshops / focus group discussions, which allowed the project team to answer the research questions for the mining sector.

The survey questionnaire consisted of 10 questions that were focused on research questions 2, 4 and 5. Stakeholder workshops were held on the 14 and 15 February 2022. The first workshop focused on the remaining economically viable minerals and was attended mostly by geologists, mineral economists and academics from various institutions. The second workshop focused on circular economy opportunities for South Africa's mining sector. The participants included environmental scientists, sustainability and climate experts, and academics from various institutions. The purpose of the workshops was to present the preliminary findings from the literature reviews conducted for research questions 1-5, validate the findings, and solicit additional information from stakeholders.

The following sections (2-6) aim to answer each of the research questions. Additional literature reviews that were essential to the understanding of the sub-topics are detailed in the Appendices. Prior to answering the research questions, it was essential to gain a deeper understanding of South Africa's mineral landscape and the mining sector's contribution to the economy through a literature review, as presented in Appendix A.

2 Years of economically viable minerals and metals for South Africa

The purpose of this section was to investigate the remaining years of economically viable minerals in South Africa. The investigation will provide an indication of the country's status regarding the availability of mineral reserves while assisting in determining whether mineral scarcity is a driver to transition to a more circular South African economy.

2.1 South Africa's economically viable minerals and years to depletion

An economically viable mineral is referred to as a reserve and is defined according to the South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC). According to SAMREC, a reserve is that part of an *in situ* demonstrated resource that can be economically extracted or produced at the time of estimation. Further explanations on how reserves are determined are included in Appendix B.

A literature review indicated that there is no data on the years to depletion of particular minerals in South Africa, in the public domain. Therefore, it was calculated using secondary mineral reserve and production data. The equation used was adopted from StatsSA as they conducted a similar exercise for gold, platinum group metals (PGM) and coal in 2017 (Equation 1). Mineral reserve and production data was sourced from different platforms such as the Minerals Council South Africa (MCSA), Statista, United States Geological Survey (USGS) and World Nuclear Association. MCSA publishes a Facts and Figures electronic document biannually that includes almost all the reserves currently in South Africa. Additionally, they also include annual production data for each commodity. The MCSA collates commodity reserve data from the USGS website which publishes commodity reserves across various countries annually. Since the data was reported in various units such as million tonnes (Mt), kilotonnes (kt) and tonnes (t), a standardized unit of million tons (Mt) was used for both reserve and production data. The mineral reserve for each commodity was reported in terms of metal content and the annual production for each commodity is reported in terms of the tonnage of the saleable product.

The equation used to determine the years to depletion is shown below (Equation 1) (Parry, 2021).

The years of depletion has been presented in ranges (based on the results) and not the exact values. The ranges were less than 20 years, 20-50 years, 50-100 years, 100-500 years and more than 500 years. A summary of the results is presented in Table 1.

It is also worth mentioning that South Africa has vast amounts of reserves of graphite and rare earth elements (REE), however these are currently not mined. The Steenkampskraal Mine in the Western Cape Province of South Africa has one of the highest grades of REE deposit in the world and is expected to re-open in the near future once the feasibility studies have been completed (Steenkampskraal, 2022). Reserves for these minerals were included in Table 2 but the years to depletion could not be calculated as there is currently no active production.

The calculated years to depletion for coal, gold and PGM was compared with that calculated by StatsSA in 2017. StatsSA calculated the years to depletion for coal to be 256 in 2017, gold at 39 years and PGM at 335 years in 2017. The values determined by StatsSA were compared with the calculated years for the same three commodities. It was found that there was a good correlation between the results.

It was acknowledged that the equation used is simplistic and does not consider various factors that may impact the calculations. The objective was to gain an indicative understanding of the years to depletion of minerals to contribute to the broader research objective of determining whether mineral resource scarcity is a driver to transition to a circular economy.

$$Years\ of\ depletion\ of\ a\ particular\ mineral = \frac{Total\ remaining\ tonnage\ of\ mineral\ reserve}{Total\ annual\ production\ tonnage\ of\ run\ of\ mine\ ore}$$

Equation 1. Years of depletion of a particular mineral (Parry, 2021)

Table 1. Summary of mineral commodities years to depletion

Range of years to depletion	Mineral commodities
< 20	iron ore, lead, manganese
20 - 50	gold, cobalt
50 - 100	zinc
100 - 500	coal, copper, PGM, vanadium
> 500	chromium, fluorspar, nickel, phosphate, titanium, uranium, vermiculite, zirconium, diamonds

The detailed reserve and production data for each mineral commodity is shown in Table 2.

Table 2. Calculated years of depletion for various minerals in 2020 using secondary reserve and production data

Commodity	Total remaining reserve (Mt) in 2020	Annual production (Mt) in 2020	Range of calculated years to depletion
Chromium	200 000	14.513	> 500
Coal	53 156	247.11	100-500
Cobalt	0.04	0.000897	20-50
Copper	11	0.029068	100-500
Diamond	130 000 000	8.471642	> 500
Fluorspar (contained CaF)	41	0.00032	> 500
Gold (metal)	0.0032	0.000096	20-50
Graphite	790 000	Currently no production	
Iron ore	690	55.635308	< 20
Lead (metal)	0.3	0,028048	< 20
Manganese (metal)	260	16,059758	< 20
Nickel	3 700	0.034908	> 500
PGM	63	0.226	100-500
Phosphate rock (contained concentrates)	1400	0.0021	> 500
REE	200 000	Currently no production	
Titanium minerals	35	0.0011	> 500
Uranium (metal, up to $US 80/kg U)	0.2791	0.00025	> 500
Vanadium (metal)	3.5	0.0082	100-500
Vermiculite	14	0.00014	> 500
Zinc (metal)	14	0.160816	50-100
Zirconium minerals (metals)	6.5	0.00032	> 500

Source: (IBM, 2020; MCSA, 2021; Statista, 2020; World Nuclear Association, 2021; Anon., n.d.; USGS, 2021)

The years to depletion values shown in Table 1 are indicative and based on our current knowledge of parameters such as current reserves, current production rates, and demand and supply. The numbers could change as parameters such as current reserves, production rates, future demand and mineral resource and reserve modifying factors change, for example, if major new reserves are found, or if prices significantly increase as demand or scarcity increases, making marginal reserves economically viable to mine.

The following assumption was made for Equation 1:

- It was assumed that reserves would only decrease and not increase in the future and annual production would remain constant for each mineral in the future.

The following limitations were identified with Equation 1:

- Equation 1 does not give a holistic indication of the remaining years of economically viable minerals due to the fact that reserves are affected by various factors which change over time, assumptions made for the calculation and limitations associated with the calculation.
- Reserves data is dynamic because reserves may be reduced as the mining of ore continues and / or the feasibility of extraction diminishes. On the other hand, reserves may continue to increase as additional known or recently developed deposits are explored. Additionally, current deposits are explored thoroughly with new technology that assists in improving and strengthening minerals economic feasibility (USGS, 2021). Mineral resources are continuously reassessed with new geological knowledge or progress in science and technology which may result in the mineral being classified as reserves (USGS, 2021).
- Reserve data should be considered a working inventory of mining companies' supplies of an economically extractable mineral commodity. As such, the magnitude of that inventory is necessarily limited by many considerations such as the cost of drilling, taxes, price of the mineral commodity being mined, and the demand for it. Reserves will be developed to the point of business needs and geologic limitations of economic ore grade and tonnage (USGS, 2021).
- Annual production of minerals is affected by geological factors (such as faults and dykes); technology used, environmental legislation and the price of the commodity.
- The years to depletion is affected by demand and supply of that particular mineral. Demand and supply are also influenced by the commodity price, the country's political status and activities, the population and weather (Wagner, *et al.*, n.d.). Undiscovered deposits (which may be considered reserves upon exploration) of minerals constitute an important consideration in assessing future supplies which will ultimately also affect the years to depletion (USGS, 2021).
- The scope of the project focused on *in situ* underground mineral reserves and did not factor in reserves in above-ground waste tailing storage facilities (TSF) and / or tailings dams.

2.2 Stakeholder engagement

This section highlights the outcomes from the stakeholder workshops. Recommendations and comments from workshop participants relating to economically viable minerals in South Africa included:

- Geological exploration has an influence on the quantity of mineral reserves. It is therefore important to gain an understanding of geological exploration currently happening within the country, even though exploration investments have plummeted throughout the years.
- To consider conducting simulations that account for changes in economic conditions or adopting technologies that allow mines to access deeper and previously inaccessible ore and determine their impact on the remaining years of depletion in the future.
- To consider including reserves in tailings dams and waste dumps as commodities to the years of economically viable minerals in future calculations. The participant mentioned that mining of old tailings storage facilities or dams / dumps have been in operation in the country and the Mineral and Petroleum Resources Development Act (MPRDA) considers tailings as a resource whereas in the Waste Act it does not, which also has implications for a circular economy.
- It was further noted by a participant that "*South Africa does not seem to have a consolidated waste reserve database therefore compiling waste reserve data may be a challenge*".

2.3 Summary and conclusion

The calculated years to depletion are indicative and based on current knowledge of parameters such as current reserves, current production rates, and demand and supply. Some of the limitations with the equation is that reserves remain constant as mining and exploration progresses. The amount of reserves may increase as the mineral resource and reserve modifying factors change. Furthermore, the demand and supply of minerals is affected by several factors such as commodity prices and emerging technologies. All of these limitations have an influence on the years to depletion values.

Three minerals (iron ore, lead and manganese) showed that they would potentially be depleted in less than 20 years of mining, two minerals (gold and cobalt) in 20-50 years, one mineral (zinc) in 50-100 years, four minerals (coal, copper, PGM and vanadium) in 100-500 years, and nine minerals (chromium, fluorspar, nickel, phosphate, titanium, uranium, vermiculite, zirconium and diamonds) would potentially be depleted after 500 years. Despite having sizeable reserves of graphite and REE, there is currently no production – despite positive growth in demand for these minerals globally. Both have an expected compound annual growth rate (CAGR) greater than 4%.

The remaining years of economically viable minerals calculations considered *in situ* underground reserves only as per the project scope. However, recommendations for future work include investigating reserves in tailings storage facilities and / or waste dumps, as mining of tailings and waste dumps may prove to be economically viable. It was further recommended that comparisons be done between the remaining years of minerals underground and in tailing storage facilities. Another recommendation was to simulate different scenarios to determine how factors such as economic conditions and adapting technologies will affect the years of depletion of various minerals in the future.

This evaluation of reserves (what appears to be the first in the public domain), raises questions around South Africa's national resource security and risk management – it is imperative to understand the available reserves and manage associated risks, as the depletion of these reserves or the non-viability to mine, places South Africa's economy at risk. The results indicating that some minerals have less than 50 years of economically viable mining remaining, raises concerns regarding mineral scarcity and its impact on the South African economy. This will be further explored in Section 5.

3 Historical demand trends on South Africa's minerals

The purpose of this section was to gain an understanding of the historical demand trends on South Africa's minerals. Production trends, and local and export sales trends, for various minerals over a period of 10 years (2010 – 2020) were analysed. The historical trends may then be compared with the future minerals of demand (critical minerals) that will be discussed in Section 4.

3.1 Production, local and export sales trends

All minerals extracted in South African mines are either sold locally or exported. Mineral exports play a vital role in the economic development of the country, and they account for approximately 66% of exports (Stats SA, 2021). In 2019, South Africa's mining industry's total income was R552.1 billion (Stats SA, 2021).

Commodities or minerals can be classified as those amenable to bulk mining or those not amenable to bulk mining. Minerals that are mostly mined in bulk are those of wide orebodies such as coal, diamonds, iron ore, and copper. Minerals of narrow-reef orebodies are not mined in bulk due to the geology and extraction method required for maximum output. These include most gold and platinum orebodies. Open cast bulk mining results in increased ore extracted at lower operational costs whilst narrow-reef underground mining produces less ore with further extraction required for the mine to be profitable (MinesFacts, 2020).

Table 3 shows the production history of various minerals (both wide orebodies and narrow-reef orebodies) from 2010 to 2016. Data for 2010-2014 was extracted from Department of Mineral Resources (DMR) and 2015-2016 data from USGS reports. The data was reported in different units, therefore some were recalculated to be shown in the standardised tonnes (t). The average annual growth rate (%) (AAGR) was calculated for each mineral using Equation 2 and Equation 3. The AAGR reflects the trend for each commodity from 2010 to 2016 and shows the average increase or decrease in production. Commodities such as coal, copper, gold and lead show an average decrease over the seven years, whilst commodities such as cobalt, chromite, diamonds, PGM and nickel show an average increase as per the results in Table 3. Cobalt showed the highest average increase of 10% whilst gold showed the lowest average decrease of -4.5%. There is no direct correlation between production and demand as demand could be increasing globally whilst South Africa's mineral production remains unchanged or declines for various local reasons.

$$Growth\ Rate\ (\%) = [(Production\ in\ year\ 2 \div Production\ in\ year\ 1) - 1] \times 100\%$$

Equation 2. Growth Rate (%) (CFI, 2022)

$$Average\ Annual\ Growth\ Rate\ (\%) = \left[(Growth\ rate)_y + (Growth\ rate)_{y+1} + \cdots (Growth\ rate)_{y+n}\right]/N$$

Equation 3. Average Annual Growth Rate (%) (CFI, 2022)

Where:

- Growth rate (y) – Growth rate in 1 year
- Growth rate (y+1) – Growth rate in the next year
- Growth rate (y+n) – Growth rate in the year "n"
- N – Total number of periods

Table 3. Production history of various minerals for 2010-2016 (DMR, 2016; USGS, 2019)

Mineral commodity	Production (t)							Average annual growth rate (%)
	2010	2011	2012	2013	2014	2015	2016	
Coal	257 205 807	250 706 255	258 575 793	255 019 489	260 642 387	252 200 000	*NA	-0.36
Cobalt	840	862	1 102	1 294	1 332	1 300	2 500	23.5
Copper	83 640	89 298	69 859	80 821	78 697	77 400	62 000	-3.9
Chromite	10 871 095	11 865 380	11 310 223	13 652 883	14 037 722	15 656 000	14 700 000	5.6
Diamonds	2	1	1	2	2	2	NA	10.0
Gold	189	180	154	159	150	144.504	142.077	-4.5
PGMs	287	289	254	264	188	276	264	1.0
Nickel	39 960	43 321	45 945	51 208	54 956	56 689	48 994	3.8
Lead	50 625	54 460	52 489	41 848	29 348	34 573	39 344	-2.4
Manganese	7 171 745	8 651 842	8 943 415	11 055 658	14 051 244	15 952 000	11 220 000	9.8
Iron ore	58 709 330	58 056 897	67 100 474	71 533 814	80 759 334	72 806 000	66 456 000	2.6
Zinc	36 142	36 629	37 034	30 145	26 141	29 040	26 695	-4.4

*NA = data not available

Local and export sales data were extracted from various yearly pocket books released by MCSA. Figure 3 shows local sales trends of various minerals from 2010 to 2020. Figure 4 shows export sales trends of various minerals from 2010 to 2020. Sales for a few minerals are shown and local and export sales data for diamonds (2010-2012) and nickel (2010-2011 and 2014-2015) are not visible on the graphs due to limited data available on public platforms. Local sales are much lower than export sales which indicates that mineral sales in the mining sector are largely export orientated.

In 2011/2012, there was labour unrest and disputes over working conditions and wages. These events had an impact on the PGM industry, particularly production thereof. The low local sales (R8 billion) and export sales (R60 billion) in 2012 compared to 2019 (R11 billion local and R124 billion exports) may be due to the aforementioned labour unrests as well as political issues, fluctuating platinum prices and low demand of PGMs (Yager, *et al.*, 2013). Local sales from 2010-2020 were largely contributed by coal with the highest sales, followed by PGM. Consistently high local sales for coal may be attributed to the fact that South Africa's electricity is mostly generated from coal and high local PGM sales may be attributed to the increased growth of car fleets (Samsodien, 2020). PGM export sales skyrocketed in 2019 reaching R124 billion in sales. This may be influenced by the increase in the value of palladium sales (R23.4 billion) and rhodium (R15.7 billion) (Stats SA, 2021). What is interesting is the fact that South Africa seemed to be producing less palladium and rhodium in 2019 than it did in other years such as 2015, highlighting the extent to which prices have driven sales growth (Stats SA, 2021).

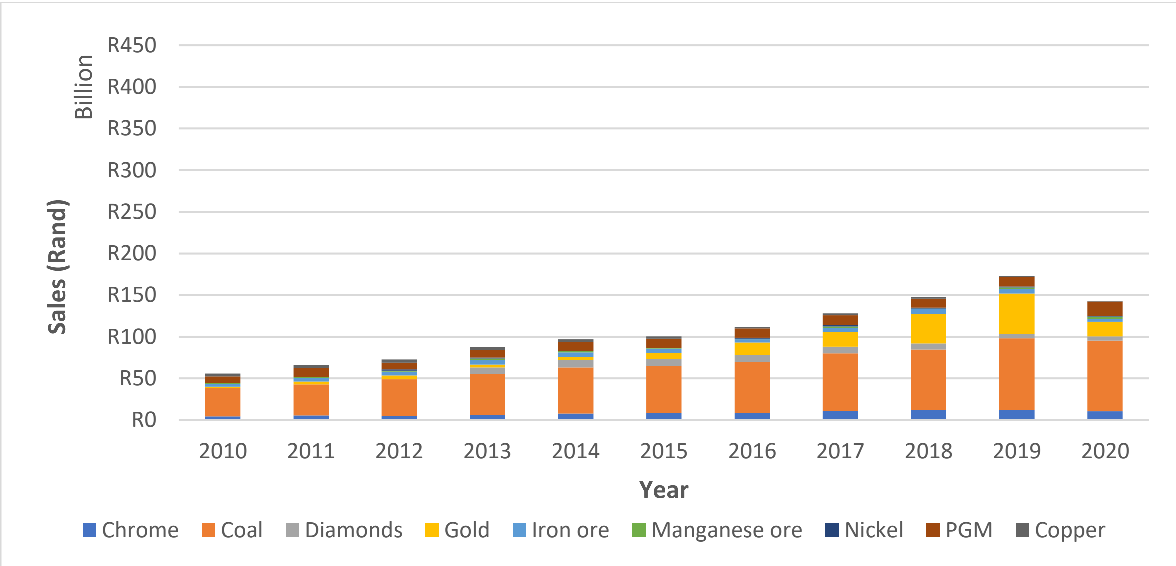

Figure 3. Local mineral sales in South Africa's mining industry 2010 to 2020 (MCSA, 2021)

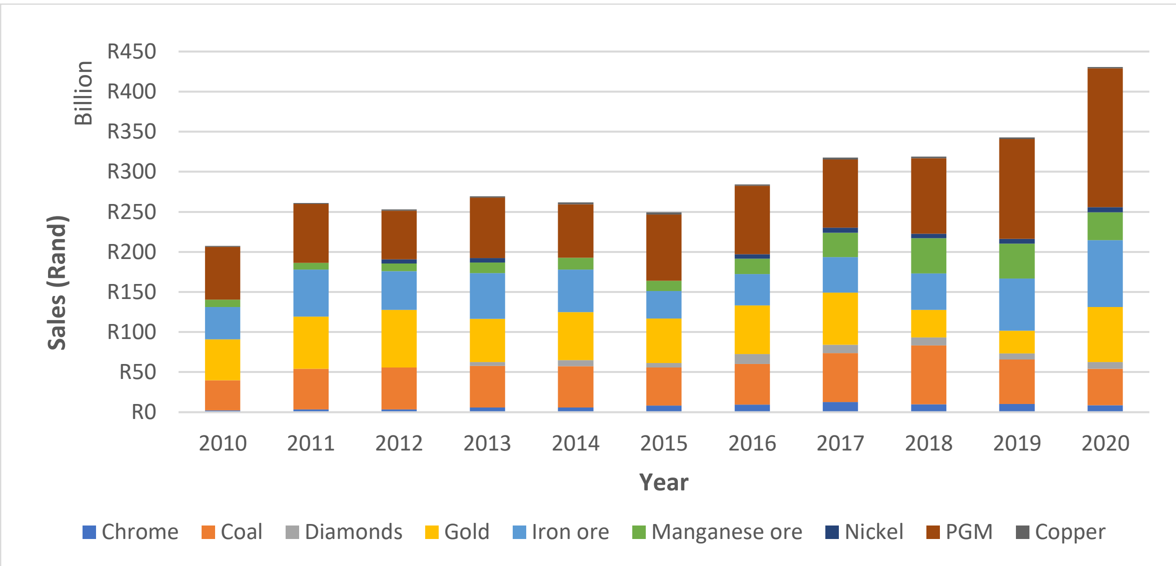

Figure 4. Export mineral sales in South Africa's mining industry 2010 to 2020 (MCSA, 2021)

Table 4 gives a breakdown of local and export sales in 2020. South Africa and the world were experiencing the COVID-19 pandemic and this resulted in mining production stoppages in the country. Mining production decreased by 51.2% year-on-year and sales decreased by 28.8% year-on-year in April, resulting from logistical constraints and internal market conditions (PwC, 2020). However, as the year progressed, commodity prices increased and were assisted by the weakening rand. The production of PGM increased by 15.5% because of an increase in PGM prices where local sales were R17.190 billion and export sales amounted to R173. billion (MCSA, 2021). Total PGM sales were higher than that for coal. The price for rhodium increased by 187.2%, making it the most expensive amongst the PGMs, a rare metal used in catalytic converters in cars (Stats SA, 2021). According to StatsSA (2021), the PGM demand (particularly platinum, palladium and rhodium) is expected to increase as countries adopt fuel cell technology in response to the call to reduce carbon emissions. It is important to note that the export of minerals is constantly changing as new markets emerge, while certain traditional export markets decline, and therefore this affects the export sales in South Africa e.g., the introduction of Battery Electric Vehicles may cause a structural demand shift as this could potentially decrease the demand for coal (IDC, 2013). Gold, iron ore, manganese, zinc, lead concentrate and PGMs indicate high export percentages of total sales. Such high export percentages means that few of these minerals end up within the local economy which may result in the mining sector having little control over circular interventions. However, it also highlights that South Africa needs to consider increased local beneficiation and local manufacturing with these minerals.

As previously mentioned, minerals that are not exported are sold and used locally. A summary of the uses of locally sold minerals are provided in Appendix C.

3.2 Stakeholder engagements

Section 3 provides a background to the trends in mineral sales (as a proxy for demand) and provides a foundation for Section 4 which also highlights future minerals demand and their linkage with specific emerging technologies. Assessing minerals demand was not a focus for the stakeholder engagement, and associated data collection, which involved stakeholder survey questionnaires and engagement workshops.

3.3 Summary and conclusion

South Africa's local and export mineral sales market contributes to the country's economy and is affected by various fluctuating factors, hence differences in sales are seen year-on-year. Sales for nine minerals (chrome, coal, diamonds, gold, iron ore, manganese, nickel, PGM and copper) were analysed from 2010 to 2020. Coal showed the highest returns from local sales and this may be due to the country's continued reliance on coal for electricity generation.

Export sales exceeded local sales which indicates that South Africa has a largely export orientated mining sector. Minerals such as gold and PGMs indicate high export percentages of total sales. High export percentages means that few of these minerals end up within the local economy which may result in the mining sector having little control over circular interventions. In 2019, PGM export sales increased the most, resulting from increased palladium and rhodium prices. Sales of minerals will continue to constantly change as new markets emerge locally and globally. However, the South African mining sector is at risk of disruption, as was evident from the COVID-19 pandemic, but may also include other global influences.

Table 4. Total mineral sales for 2020 (MCSA, 2021)

Group	Commodity	Exports sales in billion rand	Local sales in billion rand	Total sales in billion rand	Export as a % of total sales
Gold, PGMs, diamonds and silver	Gold	68	17	86	79.7%
	PGMs	173	17	190	91.0%
	Diamonds	8	5	13	61.2%
	Silver	268 152	107 169	375 321	71.4%
	Sub-total	250	40	290	86.2%
Base minerals	Chrome	8	10	18	46.2%
	Copper	1	893 016	2	63.0%
	Iron ore	83	3	86	96.2%
	Lead concentrate	690 904	3 190	694 094	99.5%
	Manganese	35	2	37	92.5%
	Nickel	6	1	7	86.3%
	Zinc	5	-	5	100.0%
	Coal	45	84	130	34.9%
	Other non-metallic	4	3	7	58.1%
	Miscellaneous	9	12	22	43.9%
	Sub-total	200	118	319	62.7%
	Grand total	**450**	**158**	**609**	**73.9%**


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4 South Africa's critical / strategic raw materials

The purpose of this section was to gain an understanding of what South Africa's critical raw materials (CRMs) are and to identify the minerals that will be important to South Africa's mineral strategy going forward. It was also aimed at determining minerals that support the economy and those that have the opportunity to further support the economy through technological innovations.

4.1 Critical / strategic minerals in SA

Critical Raw Materials: The European Union (EU) defines its critical raw materials (CRMs) as raw materials that are economically and strategically important for the European economy but may have high-risk associated with their supply (Ferro & Bonollo, 2019).

Strategic Minerals: are minerals / metals that are essential to the economy, modern technology and industry, have limited supply and are subject to disruption (SGS SA, n.d.)

In South Africa, the term strategic is generally accepted as CRMs as it refers to minerals that are of national importance whose supply is at risk. The terms 'critical' or 'strategic' minerals may therefore be used interchangeably within the context of this document, from this point forward.

In determining the critical minerals using the methodology adopted by the EU as a reference, it was discovered that the EU methodology could not be applied or adapted to the South African context due to the complexity of the variables it uses in its formulae, and the lack of appropriate local data (Appendix D). To overcome this challenge, critical minerals in South Africa were determined by linking minerals to emerging technologies. This was done taking cognisance of the fact that the world has been on a steady transition in adopting a number of disruptive technologies, such as clean energy and 4IR technologies. The intention of linking minerals with technologies was to understand which minerals will be in demand in the future in terms of socio-economic growth - GDP contribution, employment, and reducing environmental impact. Further detail relating to critical minerals and emerging technologies are provided in Appendix E.

Some of South Africa's potentially critical / strategic minerals are shown in Figure 5 and Table 5. As per suggestions from stakeholders, REEs and PGMs were unpacked into their individual elements, as presented in Figure 5 and Table 5.

The information provided in Table 5 was extracted from various sources: (Geology.com, 2022), (Anglo American, 2019), (Basov, 2022), (Yuksel, 2021), (Passels, n.d.), (Pistili, 2021), (Goodenough,, *et al.*, 2021), (Anglo American , 2015), (Us Energy Information Administration, 2022), (Britannica, 2021), (BYju's, 2022), (DMR, 2014), (Geology News and Information, 2014), (Minerals Education Coalition, 2016), (Royal Society of Chemistry, 2022), (Nickel Institute, 2022).

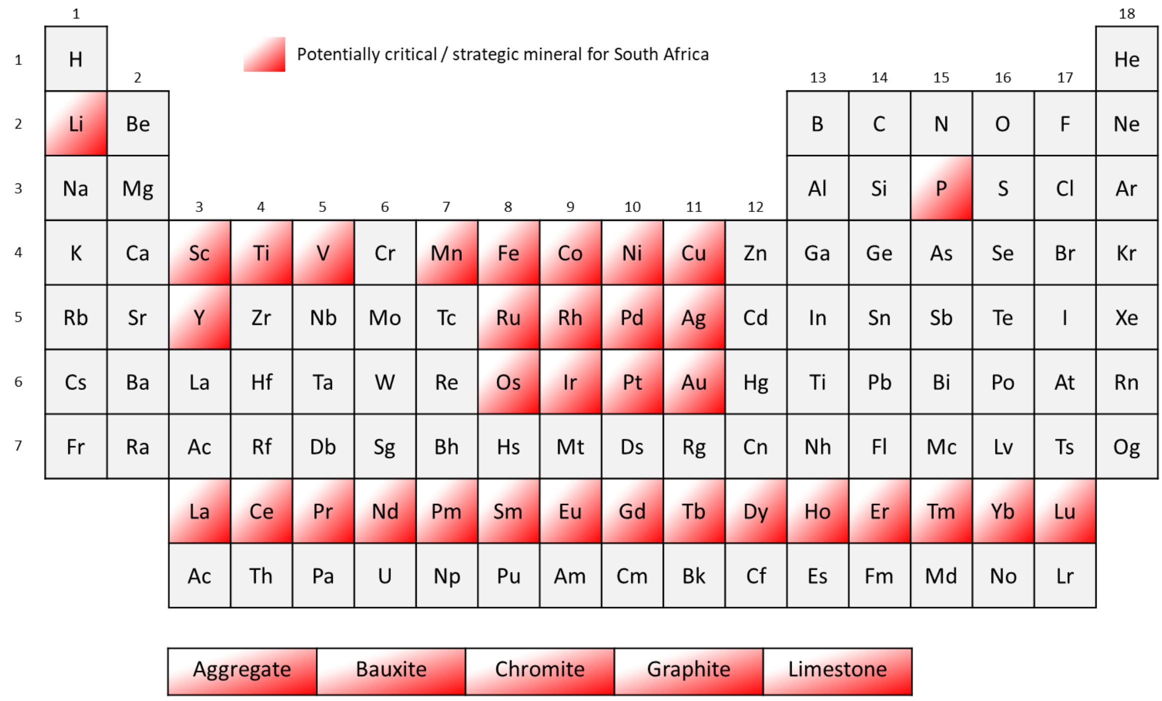

Figure 5. Summary of South Africa's potentially critical / strategic minerals

Table 5. South Africa's critical / strategic minerals

Critical / strategic minerals in SA	Justification for criticality status
Aggregates	Essential in the construction sector
Bauxite	Essential in aluminium production, metallurgy, chemical industry, and use as a catalyst. SA does not have bauxite reserves
Chromite	Essential in robotics, UAVs, steel production in SA accounts for about 70% of the world's chrome reserves
Cobalt (Co)	Essential in energy storage technology, EV economy, however, SA was ranked 10th in world production in 2020
Copper (Cu)	Essential in the solar photovoltaic (PV) cell production, electric mobility (e-mobility) industry, in drones and unmanned aerial vehicles (UAVs), remote computing and energy storage
Gold (Au)	Gold is important to the SA economy for its vital contribution to the GD, employment, and for attracting foreign capital. Scarcity of gold resources and difficulty in mining. SA was ranked 7th in production with 100 tonnes in 2021
Graphite	Essential in the e-mobility industry, however, SA has no graphite operations
Iron (Fe)	Essential in steel-making, steel is highly recyclable, reusable, and can be used for renewable energy infrastructure and transportation networks (ArcelorMittal, 2019)
Limestone	Essential in steel manufacturing, mining, paper production, water treatment and purification, and plastic production
Lithium (Li)	Essential in the green energy technologies, electric vehicles (EVs), and electronics. SA has no lithium extraction or processing, however, can play a role in the refining and processing stage (Stage 3) as a key supply chain stage. SA does not have significant lithium reserves
Manganese (Mn)	Essential in the steel industry, hydrogen fuel cells, e-mobility, and UAVs. SA contains the largest manganese reserves at 5.5 million tons and is the leading producer. However, production has decreased in 2020
Nickel (Ni)	Essential in e-mobility, drones and UAVs, energy storage
PGMs (individual elements listed below):	Often used as catalysts. SA hosts 88% of the world's PGM reserves
Iridium (Ir)	Essential in use as a hardening agent for platinum, also used in spin electronic devices
Osmium (Os)	Essential in producing very hard alloys for fountain tips, instrument pivots, needles and electrical contacts. Also used in chemical industry as a catalyst
Palladium (Pd)	Essential in catalytic convertors, cans also be used jewellery, medicine and recently started being used in fuel cells to power cars
Platinum (Pt)	Essential in motor industry with use as a catalytic convertor, also used in laboratory equipment, electrical contact and electrodes
Rhodium (Rh)	Essential in use as a catalytic convertor for cars, jewellery chemical and electrical trades
Ruthenium (Ru)	Essential in the chemical industry for coating anodes of electrochemical cells for chlorine production, can also be used in solar cells
Phosphorous	Essential in the agriculture sector for fertilizing purposes
REEs (individual elements listed below):	Essential in clean energy, defence technologies, high-tech devices, LED lighting. SA only contains about 0.7% of the world's REE reserves
Cerium (Ce)	Used in electronics like lights, TVs and ovens
Dysprosium (Dy)	Used in wind turbines, EVs and nuclear reactors when mixed within alloys
Erbium (Er)	Used in lasers and fibre optics cables
Europium (Eu)	Used in light bulbs, nuclear reactors and lasers
Gadolinium (Gd)	Used in magnets, nuclear reactors and magnetic resonance
Holmium (Ho)	Used in magnets and nuclear reactors
Lanthanum (La)	Mixed within alloys that are used in batteries and hydrogen vehicles
Lutetium (Lu)	Used as a catalyst in refineries
Neodymium (Nd)	Used in magnets and lasers
Praseodymium (Pr)	Used in aircrafts engines, fiber optic cables and magnets
Promethium (Pm)	Used in pacemakers and guided missiles
Samarium (Sm)	Used in microwave devices and devices
Scandium (Sc)	Used for fuel cells and alloys used in jet planes
Terbium (Tb)	Used in light bulbs, memory devices and X-rays
Thulium (Tm)	Used in lasers
Ytterbium (Yb)	Used in displays, x-ray machines and fiber-optic cables
Yttrium (Y)	Used in radars and as an additive within allows used in high-tech devices
Silver	Essential in alloys, batteries, light emitting diode (LED) chips, PV energy, electronics, and jewellery
Titanium	Essential in rechargeable batteries, electronics, medicine industry and EVs
Vanadium	Essential in hydrogen fuel cells, robotics and e-mobility


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Although steel is important for a low carbon and circular economy, the conventional methods of steel production contribute greatly to GHG emissions (7% of world's carbon emissions). South Africa is one of the world's largest steel producers. According to the Steel Masterplan (2019) there are plans to "green" the steel industry by using more renewable energy in production.

In determining critical / strategic minerals in this study, technological innovations and the minerals required for these technologies were investigated. It was found that sectors like energy that are focused on green energy technologies and have several initiatives that are aimed at achieving a low carbon future, and the evolution of modern technology in various sectors like mining, e-mobility and defense, are leading the change in terms of creating a demand for certain minerals and elevating their status to critical. In addition, to meet the 'critical' criteria certain minerals like cobalt, gold, iron, lead and manganese have less than 50 years of economically viable mining remaining and are thus associated with supply risk. Furthermore, some minerals such as graphite, bauxite, REEs, lithium, amongst others, are not actively mined in South Africa and may be classified as critical due to their economic importance and scarcity (supply risk).

4.2 Stakeholder engagement

Findings regarding the critical / strategic minerals showed that the list developed from the literature review was consistent with minerals that the stakeholders viewed as critical, with a few additions of minerals relating to the construction and agricultural sectors. The stakeholders highlighted the need to improve local beneficiation of resources and grow local manufacturing industries, as quoted, "*We would like to mine minerals and use them within South Africa rather than export them*."

Stakeholder comments and recommendations regarding critical minerals in South Africa, gathered through the workshops and questionnaire, included:

- The need to understand the quantity of minerals and commodities to support the transition towards a circular economy, and to ensure South Africa can manufacture and maintain technologies locally. Comments were raised regarding the methodology for determining critical / strategic minerals, on whether South Africa develops the technologies linked to these critical minerals.
- It was revealed that some of the technologies are currently used in South Africa, although not all of them. Participants further suggested that the current status of technologies in South Africa and technologies that ought to be developed be outlined, with respective required minerals.
- There were also suggestions to look into localisation and local beneficiation to leverage mineral demand through the manufacturing industry in order to reduce the heavy reliance on exports.
- One participant stated, "*We need to look at alternative uses of coal and to also consider including materials used in the construction industry in the critical minerals list, as well as aggregates, sand and limestone, and fertilisers used in the agriculture industry*." It was further advised to determine minerals that are critical to the sustainability and the development of the South African economy.
- It was suggested that the PGMs and REEs be separated into their individual elements to determine their specific use and their importance in emerging technologies.
- Participants further emphasized the importance of localisation and beneficiation, highlighting the importance of drawing the link with manufacturing and metals since the demand for certain minerals will be driven by the technologies regardless of whether certain minerals are produced locally or exported.
- Although South Africa remains in support of greater local beneficiation, one participant stated, "*It is likely we will remain a net exporter of a lot of our new resources*."
- It was highlighted that many people approach the circular economy from the perspective of trying to find ways to keep the existing economy going in its current state. However, it was suggested that the circular economy be investigated in greater depth in terms of developing a new economy. A participant stated, "*We should be looking at material replacement and finding alternative materials, understand which minerals are here, how we can mine them and apply them to modernisation principles to stretch into a lifetime*." Furthermore, it was emphasised that replacements should be identified for the high supply risk minerals.

4.3 Summary and conclusion

There is a need to improve data collection and reporting (in the public domain) in the mining sector. This will allow for improved future calculations and reporting on South Africa's critical raw materials, in order to better manage national development risks.

The global uptake of disruptive technologies, such as decarbonisation and 4IR technologies, has created a demand for minerals globally. The list of critical minerals in South Africa was determined based on the minerals required to develop and operate these technologies. It was, however, noted from stakeholder engagements that there are minerals that could also be considered critical in terms of the economic importance to industries like construction and agriculture. Some minerals that were classified as critical in South Africa have less than 50 years of economically viable mining remaining (cobalt, gold, iron ore, lead and manganese), therefore, it is crucial that they be extracted and utilised in a sustainable manner to ensure that current and future demands are met. Although adopting circularity within the mineral value chain may be a potential solution for sustainable resource use, these minerals are mostly exported, suggesting that South Africa may have little control over their downstream circularity. Therefore, it is recommended that local beneficiation and local manufacturing should be prioritised so that South Africa may realise the benefits of its own resources. Additionally, the idea of resource leasing as opposed to resource sales to trading partners may be further explored as a potential means to encourage responsible and sustainable resource use.

From Section 3, it can be seen that coal contributed to consistently high local sales over the past 10 years (Figure 4, Section 3.1). Coal, however, does not feature on the list of South Africa's potentially critical / strategic minerals. This raises concerns over the fact that the just-transition to cleaner and greener energy may reduce the demand for coal. There is therefore an urgent need to consider alternative uses for coal and coal discards, if appropriate, so that economic benefit from coal resources is not completely lost.

Furthermore, Figure 4 (Section 3.1) indicates that export sales of PGM increased steadily from 2017 to 2020, suggesting that there is an increasing demand for PGM globally. It thus becomes increasingly important to prioritise local beneficiation and manufacturing and to promote sustainable resource (PGM) use to meet future local and global PGM demands.

Key suggestions from the stakeholder engagements regarding critical / strategic minerals are summarised below:

- Investigate alternative or replacement materials for those minerals that are at high risk of depletion.
- Be mindful of the possibility of locking ourselves up in the existing export model by not focusing on local economic development through localisation.
- Localisation and beneficiation must be at the forefront of a circular economy even though it is expected that more minerals are still going to be exported than used locally.
- REE and PGMs must be looked at individually to determine the criticality and application of each element to contribute to further economic growth. Although the relevance of REE to South Africa has been recognised, the challenges associated with mining of REEs include supply chain, processing, environmental and geopolitical issues (Jellicoe, 2019).
- Investigate alternative industries / economies that might arise with these emerging technologies, which may in turn unlock new, local employment opportunities.

5 Resource scarcity as a driver for South Africa to transition to a circular economy

5.1 Resource scarcity as a driver for a circular economy in South Africa

Globally, the economy has historically adopted a "take-make-waste" linear model that is dependent on the excessive use of finite resources resulting in the risk of resource shortage and ultimately depletion (Melati, *et al.*, 2021). With material consumption set to drastically increase with evolving technologies, resource shortage is bound to occur as the number of resources required to meet global demands is estimated to be triple the current amount by 2050 (Govindan, *et al.*, 2015). With this reality in sight, the circular economy may offer alternative solutions that will ensure economic and environmental sustainability and the responsible consumption of natural resources. Resource scarcity results in fluctuating raw material prices and uncertainty in availability. As a result, the circular economy offers an alternative option by finding ways to keep materials in use for as long as possible (PwC, 2019). Companies like Apple, for example, are following suit by using recycled materials such as aluminium, copper, tin, and tungsten in their electronic devices.

According to the results from a survey by the OECD (2022), additional drivers for a circular economy transition include climate change, global agendas, economic development, job creation, private sector initiatives, new business models, technological developments, and research and development (OECD iLibrary, 2022). South Africa is a nation that has been reliant on the mining of finite mineral resources for over a century, to support economic development, but will face future risks associated with resource scarcity and security (Fedderke & Pirouz, n.d.).

Ultimately, research questions 1 and 2 showed that certain minerals like cobalt, gold, iron ore, lead and manganese have less than 50 years of economically viable mining remaining, assuming all else remains constant. Based on research question 2, these minerals may be classified as critical / strategic in South Africa. These results, together with the fact that all minerals are finite and non-renewable resources that will eventually be depleted, raises concerns that mineral resource scarcity may in fact be a driver for South Africa to transition to a more circular economy, with a combination of other factors.

It may therefore be conceded that the transition to a more circular South African economy provides a means for the country to manage its future development risks through the sustainable and efficient use of finite resources, with a focus on greater local beneficiation, use and circularity.

5.2 Stakeholder engagements

Recommendations and comments from survey questionnaires and from the stakeholder workshops included:

- "*The level of resource scarcity is dependent on technologies and economics of today. If these dynamics change, the transition to a circular economy may be put in peril.*" A suggestion was to consider putting the circular economy forward from a growth and job creation perspective in South Africa.

- It was highlighted that even though South Africa is a resource-rich country, the question of whether resource scarcity is the driver to transitioning, has not been the easiest to answer. The circular economy emerged globally within the context of resource scarcity, but the focus has now shifted. The participant stated, "*I think since then it's shifted very much into whether transitioning to a circular economy creates opportunities for climate change mitigation, and when the pandemic hit (COVID-19), it became transitioning to a circular economy creates an opportunity for green economic recovery, job creation, new business development and I see now that the discussion has moved further to sustainable production and consumption.*"

- It was further highlighted that in cases where South Africa has thousands of years of resources remaining, resource scarcity cannot be the driver for the transition and in that case, the next step is to understand the number of new local businesses and jobs that could be unlocked through the circular economy.

- Participants questioned whether the transition to a circular economy is more focused on climate change mitigation, renewable energy drive, and sustainable consumption. There were also suggestions to identify exploration opportunities by rebuilding core businesses around scarce resources and taking advantage of the green energy transition.

- A participant commented on how transitioning to a circular economy will provide opportunities for mining communities to benefit from operations. These benefits can be environmental, economic, and social through the creation of value networks. A suggestion was to map the values (skills) of the community that may enable them to become involved in the circular economy transition.

- Inputs from the questionnaire included:
  - The driver for the transition to a more circular economy is not limited to one factor but several factors including the need to optimise processes and materials, waste valorisation, limited availability of key resources such as REEs, climate change goals, supply security, economic growth, employment opportunities, population growth and energy demands, need for greater energy mix, increased materials demand as a result of low carbon economy drive, need for materials reuse / recycle to meet future demand, waste reduction, and the need to reduce mineral imports.
  - "*Optimising the recovery of secondary resources from waste electrical and electronic equipment (WEEE) and systematically finding opportunities for urban mining to replace the need for primary minerals extraction. There is a need to secure CRM supply for SA to be able to undergo our own green energy transition and ensure we do not become a mere supplier of valuable resources for the Global North to fulfil their ambitions - renewable energy targets linked to exploiting hydrogen, solar and wind and introducing en masse electric vehicles*."

5.3 Summary and conclusion

In answering the question of whether resource scarcity is a driver for South Africa to transition to a more circular economy, several factors were considered. Literature reviews, research questions 1 and 2, and stakeholder inputs were collectively analysed to determine whether resource scarcity is in fact a driver for South Africa. The nature of minerals which are finite and cannot be replaced once mined, were a major factor. Additionally, considerations included the demand level of certain minerals as a result of modernisation, low-carbon goals, and sustainable mining.

Research questions 1 and 2 showed that certain minerals like cobalt, gold, iron ore, lead and manganese have less than 50 years of economically viable mining remaining. Based on research question 2, these minerals may be classified as critical / strategic in South Africa. These results, together with the fact that all minerals are finite and non-renewable resources that will eventually be depleted raises concerns that mineral resource scarcity may in fact be a driver for South Africa to transition to a circular economy. It can therefore be argued that all mineral commodities are scarce and should be used sparingly and in a sustainable and responsible manner, for the benefit of present and future generations. Urgent priority should be directed to those commodities that may potentially be depleted within the next 50 years of extraction by identifying and investing in local circular economy interventions for these commodities.

Based on stakeholder engagements and questionnaire responses, the transition to a more circular economy may also be driven by several factors besides resource scarcity as some of the minerals still have hundreds of years of economically viable mining remaining. Job creation, environmental factors, green energy transition, and economic growth are among the contributing drivers.

Overall, there was a general consensus from the stakeholders that resource scarcity is in fact one of the drivers for South Africa to transition to a circular economy, however, other factors can be considered as the main drivers like job creation, socio-economic factors, climate change commitments, and business objectives, amongst others.

Some of the key recommendations from the stakeholder engagements are summarised below:

- Investigation of gradually developing core business in mineral exploration where there is resource scarcity.
- The DMRE to consider developing a Circular Economy Strategy or Policy for the South African mining industry.
- Investigate ways in which the mining industry can take advantage of the renewable energy transition.
- Core businesses in the mining industry to consider shifting to secondary resource optimisation.
- South Africa to consider energy and circular economy transition relationships and investigate new trading models with trading partners to avoid compromising its own future.
- Consider strategies for leasing mineral resources to trading partners instead of selling them, to ensure sustainable and responsible use thereof.
- Rethink how communities can be involved in the transition to a circular economy because they potentially have value that can be incorporated in the process. There is an opportunity to map out the values / skills of the communities which may enable them to become involved in the transition to a circular economy.

6 Circular economy opportunities for the mining sector

6.1 Circular economy principles

The circular economy is underpinned by three principles (DST, 2019; ACEA, 2018; ICMM, 2016):

i. Designing out waste and pollution, e.g., redesign mining processes and value chains to be more resource efficient;
ii. Keep products and materials in use, e.g., reduce, reuse and recycle various waste streams, including end-of-life equipment; and
iii. Regenerate natural systems, e.g., renewable energy, restoring mining landscapes.

The circular economy opportunities in the mining sector, as identified together with stakeholders, have been categorised in the following subsections according to the three circular economy principles.

6.1.1 Designing out waste and pollution

6.1.1.1 Increased ore extraction efficiency and precision

New and emerging technologies could be explored for increased precision and efficiency of ore extraction, with minimal energy usage, reduced water and capital intensity and less waste production in the process. For example, coarse particle recovery, bulk sorting, ultrafine recovery, fracking and *in situ* mining (Anglo American, n.d.). Efficient extraction involves a more complete extraction of the ore, extending the life of mining operations, and increasing the range of mineral recovery. Not only does this reduce the need to open new greenfield mines, thereby minimising the environmental footprint, but it provides diversified opportunities for economic return.

6.1.1.2 Water recovery and recycling

Reducing dependence on fresh water in mining operations may contribute positively to our ecological system. Possible innovative technologies for water recovery and recycling include dry processing, evaporation management, novel leaching, and dry stacking. This will also eliminate the need for wet tailings storage facilities and instead create stable, dry, and sustainable land.

6.1.1.3 Substitution of raw materials

Substitution of raw materials where possible could potentially minimise the overall production of waste and reduce carbon emissions from excessive mining operations. An example is the use of thiosulphate leaching as an alternative to cyanide in gold processing.

6.1.2 Keep products and materials in use

6.1.2.1 Reduce, reuse and recycle

The majority of South African mines currently adopt the "*keep materials in use*" principle, which comprises some of the following initiatives:

- Reduce (waste management) – Anglo American's Kumba Iron Ore advanced from this practice by embracing the circular economy concept. They are currently embarking on an intensive waste management strategy called 'zero-waste-to-landfill' that aims to eliminate unnecessary waste from reaching landfills, according to their 2020 sustainability report. This initiative may also be categorised under the 'design out waste' principle (Anglo American, 2020).

- Re-use (or repurpose) – Examples of contribution of mining to the circular economy, through reuse and repurposing of mine waste include (Lottermoser, 2011, ICMM, 2016):
    - Use of waste rock for various applications such as backfilling mined out areas, buttressing of highwalls, landscaping, aggregates for construction, raw material for cement manufacturing and reprocessing to extract remnants of valuable minerals;
    - Use of manganese tailings in agroforestry and for producing coatings, resin, glass and construction materials;
    - Use of clay-rich tailings for production of bricks, floor tiles and cement;
    - Use of slag in production of concrete and cement, and in road construction;
    - Use of bauxite red mud as feedstock for glass, ceramics and brick manufacturing, and also for soil and wastewater treatment;
    - Use of mine water for a number of applications including dust suppression, mineral processing, cooling, source of drinking water, and other industrial and agricultural uses; and
    - Use of iron rich sludge from acid rock drainage treatment for making pigments.

- Repurposing of old tyres is also another intervention that some mines adopt, although challenges are still prevalent.

- Recycle (management of tailings storage facilities) – the management of hazardous waste material in tailings storage facilities is evolving, owing to technological developments and innovation to minimise waste and maximise resource efficiency. Re-treatment and re-mining of tailings has also gained traction in recent years. For example, Sibanye-Stillwater's West Rand Tailings Retreatment Project (WRTRP) not only proved to be economically viable, but benefits all stakeholders, communities and the environment (Sibanye Gold, 2016).

Other companies that mine gold waste rock dumps in SA are DRDGOLD, Mintail and Goldfields.

- In the aluminium industry, consumers are trending towards recycling of scrap metal after the COVID-19 pandemic impacted the supply chain for bauxite imports. There is huge potential for the use of aluminium in the circular economy as it is a 'green metal' with the ability to be recycled multiple times without losing its original properties (European Aluminium, n.d.).

6.1.2.2 Processing of residues and secondary metals

Apart from trying to reduce waste generated from mineral processing related activities such as smelting and refining, further circular economy opportunities can be harnessed from processing of residues and secondary metals, and some practical examples under this focus area include (ICMM, 2016):

- Use of scrap in combination with primary concentrates to produce metals;
- Secondary smelting of electronic scrap to produce valuable metals such as gold, silver, copper and palladium;
- Optimising the recovery of co-products. For instance, a nickel mining company can increase the recovery of co-products such as PGM, cobalt and copper;
- Reducing the amount of acid gases emitted into the atmosphere by manufacturing sulphuric acid using the off-gas cleaning process in primary smelters; and
- Incorporation of acid plants into the smelting process, to convert sulphur dioxide to sulphuric acid.

6.1.2.3 Urban mining of e-waste

Alternate business models and subsequent jobs may potentially be created by existing mining companies through the recovery of end-of-life products and/or e-waste (urban mining). This could be done by establishing subsidiary companies that recover scrap metal and reprocess them. As at 2018, less than 10% of e-waste was collected for recycling, most of which was then exported and processed internationally. Local universities and science councils are currently undertaking research on developing appropriate technologies to recover and process metals from printed circuit board waste. A chemical extraction process for copper using ammonium sulphate is included as part of the investigation. The project is expected to be piloted in 2022 (Eco Africa, 2021).

6.1.3 Regenerate natural systems

6.1.3.1 Renewable energy

The integration of renewable energy such as solar, wind, and hydrogen (green energy) to power mining operations will reduce energy consumption, costs and carbon footprint. Gold Field's Westonaria mine plans to move towards 20% solar powered operations by 2022 to partially mitigate the impacts of Eskom's unreliable supply (Phillips, 2021).

6.1.3.2 Green hydrogen production

Green hydrogen production has huge economic potential for South Africa, which would consequently result in increasing demands for PGMs - Platinum is used as a catalyst in fuel cells (Hinkly, 2021).

The advent of hydrogen production may allude to the adoption of fuel cell technologies in the country. Fuel cells are used in EVs. Mining companies such as Anglo American and Impala Platinum have already adopted the use of fuel cell electric vehicles (FCEV) at South African mining operations. The Paris Agreement binds South Africa to strive for zero carbon power (hydrogen, solar and wind). The production of green hydrogen requires renewable energy (solar and wind power), both of which are vast in South Africa. This positions South Africa favourably and has potential for its economy in the future - decarbonisation of its local economy and exporter of green energy (PwC, n.d.).

6.1.3.3 Repurposing of post mining landscapes

Old mine sites could potentially be rehabilitated and repurposed as educational training centres, agricultural land (e.g., wheat pilot project in Mpumalanga), or tourist attractions (e.g., museums or theme parks). Examples of old mines repurposed as tourist attractions is Gold Reef City in Johannesburg and The Big Hole in Kimberly.

6.1.3.4 Eradication of alien invasive plants for water reutilisation

South Africa's Working for Water (WfW) programme aims to accelerate the eradication of invasive biomass. 2.9% to 6% of water is captured by alien invasive plants – when removed, water may be released for other uses (Department: Environment, Forestry and Fisheries, 2022). For mines, this water may significantly benefit the company and the communities if the invasives were to be cleared around the mines. It may also provide the opportunity to use natural, regenerative systems to treat mine waters, e.g., natural wetland systems, which contribute to local ecosystem services.

6.2 Stakeholder engagement

Inputs solicited through stakeholder workshops and questionnaires regarding circular economy opportunities for the mining sector included some of the following points made by the stakeholders:

- A great missed opportunity with regards to repurposing of post-mining land and the green hydrogen area is the use of natural resources, specifically invasive alien biomes. It is seen as a liability but may be transformed into an asset. They act as erosion blankets but can be used to restore mining land. When land is cleared it can be used for agriculture. It can also be beneficiated into products that can restore mined out land, such as soil sausages, erosion blankets and as an input into green hydrogen production. When the invasive plants are removed there is a release of water that can be reused. Clearing of invasives also implies a compliance box is being ticked. There is the potential to set up a virtuous or circular economy cycle by clearing out invasives.

- Another potential opportunity is the development of technologies and utilisation of mining waste for carbon capture, e.g., in waste rocks such as Kimberlite. Studies are currently being undertaken in this area.

- Biotechnology may be used to recover metals from appliances, cellphones, etc. An example is bioleaching whereby bacteria may be used to open up minerals such as pyrite.

- Kumba Iron Ore is implementing ultra-high dense medium separation technology – recovering iron ore from what was previously classified as "c-grade" material (previously waste), whereby "a" and "b" grades are the best.

- In terms of zero waste to landfill strategies, Kumba Iron Ore does bioremediation whereby they remediate hydrocarbon contaminated soils. There is insufficient topsoil at their current operations and topsoil is required for rehabilitation. Instead of disposing these soils as hazardous landfill sites, bioremediation facilities were constructed whereby bacteria is used to remediate the soil which is then used for rehabilitation.

- There is a need to consider biomimicry for sustainable solutions to waste management. A participant stated, "*We need to look closely at biomimicry because there is a fungus or a bacterium for any type of man-made pollution. It has not really been looked at in the amount and the extent that we should. They are nature's solutions*." Another participant added that technology was developed by the Japanese and is now being used in South Africa.

- It is important to factor in life cycle assessments when dealing with waste generated by mining. It is becoming increasingly important to deal with waste issues due to the changing policy landscape around waste and environmental issues. Instead of waiting till the end when it will be more expensive and as legislations develop, it should be dealt with upfront. Another participant supported the idea of more realistic life cycle assessments and stated, "*We have very good legislation, e.g., the MPRDA in terms of environmental and social aspects and rehabilitation after mine closure. Compliance and enforcement of the legislation is an issue. Most mining companies avoid mine closure*."

- In terms of the potential to scale up some of the circular economy interventions, a participant indicated that zero-waste-to-landfill programmes could be implemented at many more mines based on learnings from the current strategy by Kumba Iron Ore.

- In order to drive the circular economy forward in the South African mining sector, life cycle assessments of various mining aspects are crucial. A participant stated, "*There is a need to uncover what the hidden external costs are and from a triple bottom line approach. There will be more urgent interest from the mining industry if those external costs that are currently hidden are fully uncovered*."

- Some of the circular economy opportunities highlighted in response to the questionnaires included:
  - Integrated mining through waste recirculation for energy generation
  - Re-use of effluents to extract trace amounts of metals
  - Extraction of minerals from sewage
  - Reuse and recycling of infrastructure materials
  - Re-processing of waste and discards
  - Reclaiming of e-waste and supporting this industry in extraction of metals
  - Understanding demands in low energy economy and changing needs of raw material supply as technology develops
  - Understand what metals and elements can in fact be reused / recycled
  - Creating economies of scale in the Southern African Development Community (SADC) region for WEEE collection, in collaboration with South Africa, thereby developing end-processing capacity for metal refining. This would make Africa less dependent on foreign smelters and retain valuable resources on the continent. This would unlock opportunities to plan ahead in terms of the continent's own

much required green energy transition (with SA being 12th worst CO_2 emitter currently)
    - Reskilling of miners into refurbish and repair and value fraction recovery experts

- Pockets of excellence in adopting circular economy principles in South African mining companies include:
    - A small start-up, 'pure' copper production company, *Big Tree Copper,* in the Northern Cape remines the waste at the decommissioned Okiep Copper mine. They are the only pure copper mining company in South Africa. According to the Mining Weekly (2022), Big Tree Copper is a dump retreatment business and not a mine, and do not have the same corporate social responsibilities as a mining company.
    - The *Green Engine* is an Anglo American Coal SA Lighthouse project to reduce waste and extract value. It has the potential to address the sustainable development goals (SDGs) and support the transition from coal-powered energy to renewable energy. The Green Engine is aimed at sustainable mine closure through mine rehabilitation and water management strategies that benefit communities and the environment (Anglo American, 2020).

6.3 Challenges

One of the biggest challenges is the large volume of waste (waste rock and tailings) generated from upstream mining activities. Even though opportunities to reuse and repurpose waste exist, the rate of reuse and repurposing cannot keep up with the rate at which waste is generated.

Segregation of non-hazardous waste is also a challenge being faced by Anglo American while undertaking their largely successful zero-waste-to-landfill strategy (Anglo American, 2020). They found that certain waste streams may prove to be challenging as not all waste can be recycled due to limited technological developments.

Recycling of mining vehicle tyres has also presented some challenges due to their large size, making them difficult to manage. In 2020, Kumba Iron Ore stored about 20 000 tons of scrap tyres, ready for sustainable disposal. Continuous efforts to resolve the issue are being made by Kumba Iron Ore (Anglo American, 2020).

Although some of the circular economy opportunities presented above make financial and environmental sense, they are not always operationally possible to implement. For example, although backfilling of waste rock is not a new concept, some mines still encounter challenges in this regard due to the mining method being used. Some mines undertake 'selective mining', whereby different ore grades are mined from different areas within the pit at different times, depending on the demand for the minerals. This means that one particular area is not completely mined out such that it can be backfilled by waste rock upon 'completion' of mining. This results in huge stockpiles of waste rock above ground. Research, development and innovation (RDI) would be key to tackle the challenges and assist with implementation of these opportunities.

Even though many mining companies already adopt some elements of a circular economy, it is not being done at a scale large enough to make a meaningful impact on the economy or on the environment. Scaling up circular economy interventions are therefore important for the mining sector (and the country) to realise a significant impact.

Implementation of some circular economy solutions are costly. Mining is largely driven by economic profit, legislative compliance or corporate social responsibility; therefore, mining companies need a very good reason to adopt some of the practices.

While reducing, re-using, and recycling of materials is highly feasible to adopt, the 'high impact' principles of regeneration of natural systems and designing out waste require large investments, often making them difficult and slow to implement (ACEA, 2018). This highlights the importance of incentivising mining companies to adopt circular economy principles in addition to the inclusion of the circular economy in mining legislation.

For longer term opportunities such as urban mining of e-waste, the challenges include administration associated with the characterisation of hazardous e-waste. It is a complex waste stream therefore one needs to be careful about how it is done, as South Africa may end up exporting those value fractions.

6.4 Summary and conclusion

The most implementable circular economy opportunities in the mining sector are those aligned with the "*keep materials in use*" principle. These include reducing, reusing and recycling of materials. Although some of the opportunities mentioned within this category are not new concepts, challenges still remain when it comes to implementation of these initiatives. The challenges are mainly operational and financial, suggesting that RDI are key focus areas to addressing these issues.

In terms of financial constraints to implementation, the cost versus long-term benefit of these interventions needs to be better understood and realised. Even though some mining companies adopt circular economy principles, the interventions need to be scaled up to make a meaningful impact on business, society, environment, and the economy at large.

7 Conclusion

The project objectives were achieved by answering five research questions relating to (i) the economically viable minerals remaining in South Africa, (ii) determination of South Africa's critical / strategic minerals, (iii) historical mineral demand trends, (iv) resource scarcity as a driver for South Africa to transition to a circular economy, and (v) the potential circular economy opportunities for the South African mining sector. This was done through literature reviews, stakeholder engagements and questionnaires.

The results obtained from calculating the remaining years of economically viable minerals in South Africa indicated that some minerals have less than 50 years of economically viable mining remaining which raises concerns regarding mineral depletion and its impacts on the South African economy. Although adopting circularity within the mineral value chain may be a potential solution for sustainable resource use, these minerals are mostly exported, thereby imposing limitations on the country's ability to put circular interventions in place that benefit the local economy. It is therefore recommended that local beneficiation, use and circularity be prioritised so that South Africa may fully realise the benefits of its own resources.

Analysis of the historical mineral demand trends showed that coal had the highest returns from local sales, which may have been due to the country's continued reliance on coal for electricity generation. In 2019, PGM export sales increased the most, which is likely due to increasing developments in clean energy and 4IR technologies that tend to increase the demand for critical minerals.

Eighteen minerals were identified as critical / strategic in South Africa due to their economic importance and supply risk. The critical minerals in South Africa include: aggregate, bauxite, chromite, cobalt, copper, gold, graphite, iron, limestone, lithium, manganese, nickel, PGMs, phosphorous, REEs, silver, titanium, and vanadium.

The just-transition to renewable energy necessitates investigations into alternative uses for coal so that the economic benefit that South Africa currently gains from coal sales is not completely lost. Additionally, to avoid locking South Africa into an export model, local beneficiation and manufacturing of PGM (amongst other minerals) becomes increasingly important as the demand for critical minerals increases.

Based on the findings, it was concluded that resource scarcity may in fact be a driver for South Africa to transition to a circular economy. However, other drivers also need to be considered such as job creation, socio-economic development, climate commitments, and business objectives, amongst others. It can therefore be argued that all mineral commodities are scarce and should be used sparingly and in a sustainable and responsible manner, for the benefit of present and future generations. Urgent priority should be directed to those commodities that may potentially be depleted within the next 50 years of extraction – cobalt, gold, iron-ore, lead and manganese – by identifying and investing in circular economy interventions for these commodities.

The most implementable short-term circular economy opportunities in the mining sector are those within the "keep materials in use" principle. These include reducing, reusing and recycling of materials. Although some of the opportunities mentioned within this category are not new concepts, challenges still remain when it comes to implementation of these initiatives. The challenges are mainly operational and financial, suggesting that research, development and innovation are key focus areas to addressing these issues. In terms of financial constraints to implementation, the cost versus long-term benefit of these interventions needs to be better understood and realised. Even though some mining companies adopt circular economy principles, the interventions need to be scaled up to make a meaningful impact on business, society, environment, and the economy. A considerable number of circular interventions have been identified for the mining sector, some of these may require time to implement, making them more suitable for medium- to longer-term implementation.

The study has also highlighted evidence gaps, where further research is needed, including:

- Improvement of data collection and reporting on South Africa's mineral resources, to ensure that the associated risks around resource scarcity and resource security are appropriately managed;
- Investigation of alternate uses of coal and coal discards (as appropriate);
- Identification of replacements / substitutes for critical minerals;
- Investigation of alternative industries / economies that might arise with emerging technologies, which may in turn unlock new employment opportunities;
- Consolidation of a database for reserves of tailings and waste rock dumps in South Africa;
- Investigation of ways in which the mining industry can take advantage of the renewable energy transition;
- Development of a framework for transitioning core businesses in the mining industry to secondary resource optimisation business models;
- Development of new trading models with trading partners in consideration of the energy and circular economy transition;
- Assessment of strategies for leasing mineral resources to trading partners instead of selling

them, to ensure sustainable and responsible use thereof;
- Assessment of communities-inclusion in the transition to a circular economy and mapping out the values / skills of the communities which may enable them to become involved in the transition to a circular economy;
- Development of technology to utilise waste to capture carbon (e.g., in Kimberlite waste rock);
- Assessment of the use of biotechnology and biomimicry to recover valuable metals from appliances and electronics and for sustainable solutions to waste management;
- Detailed cost analysis of circular economy interventions for the mining sector;
- Investigation of potential management strategies for waste streams that are difficult to recycle (e.g., large tyres);
- Large-scale implementation of zero-waste-to-landfill programmes (and other short-term circular economy interventions) at South African mines; and
- Addressing operational barriers to implementation of circular economy interventions (e.g., backfilling of waste rock into mined out areas).

The gaps identified in this study and the recommendations made by the stakeholders requires further analysis to create a roadmap for the circular economy in the South African mining sector.

The findings of the study suggests that the circular economy has the potential to unlock opportunities for the South African mining sector, which include new business models for mining companies and communities, inter-sector collaboration, job creation, technological innovation, reskilling of people and climate mitigation.

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Appendices

Appendix A – South Africa's mineral landscape

South Africa is a mineral rich country that has a broad Mining and Metals Sector (MMS) with various mining activities. According to MQA (2021), the MMS consists of nine subsectors which are spread over nine provinces. The subsectors are Cement, Lime, Aggregates and Sand (CLAS); Coal Mining; Diamond Mining; Diamond Processing; Gold Mining; Jewellery Manufacturing; Platinum Group Metals (PGMs); Services Incidental to Mining; and Other mining which includes the mining of iron ore, chrome, manganese, copper, and phosphates (MQA, 2021).

The MMS has been one of the major pillars of the South African economy for more than a century (MCSA, 2020). The combined sector provides both direct employment (in mines) and indirect employment (engineering, services etc.) (SAMCODES, 2016). The MMS employment is approximately 451,427 workers and most of the workers are employed in the PGM (163,538 workers), gold (93 682 workers) and coal sectors (91,459 workers) (Statista, 2021). Table 6 shows a commodity contribution to employment from 2009 to 2019. In 2009, 2011 and 2012, gold employed the most workers amounting to 159,926, 144,799 and 142,200 respectively.
Other notable contributions of the mining sector to the South African economy during the year 2020 include (MCSA, 2021):

- R608 billion total in primary mineral sales;
- R575.1 billion minerals export sales;
- R11.8 billion in royalties;
- R27.2 billion in company taxes;
- R148.5 billion in employee earnings; and
- R361.6 billion direct contribution to the gross domestic product (GDP) representing a total of 8.0%.

Figure 6 depicts the distribution of various mineral commodities across the nine provinces of SA. The country is endowed with resources of various mineral commodities such as gold, platinum, coal, diamond, copper, chrome, iron, lead, manganese, nickel, titanium, vanadium, zinc, andalusite, fluorspar, phosphate, vermiculite, asbestos and uranium. Major mining activities occur in Limpopo (coal, PGM and 75% of the world's total chrome in the Steelpoort Valley), Mpumalanga (coal and PGM), Northern Cape (diamond, iron ore and manganese) and the North-West Province (PGM, diamond, and gold) (PwC, 2020).

SA has been ranked fifth internationally with regards to its mining contribution to the country's (GDP (Wits Mining Institute, 2020). Of the known reserves in the world, Wits Mining Institute (2020) noted that SA hosts 88% PGMs, 80% manganese, 75% chromite and 13% gold reserves. It is noteworthy that SA was ranked as the world's number one in terms of PGM, manganese, chromium and gold deposits. It has also been ranked second in titanium minerals (10%), Zirconium (25%), Vanadium (32%), Vermiculite (40%) and Fluorspar (17%) reserves and it contains 17% of the world's antimony reserves (Wits Mining Institute, 2020). PGMs constitute of platinum, palladium, rhodium, iridium, osmium and ruthenium but platinum, rhodium and palladium are of most significant economic value (NMA, 2016).

Gerard (2021) mentioned that SA holds approximately R35 trillion worth of mineral resources which have not been exploited yet. Even with the country's mineral wealth, it has been years since SA attracted sufficient investment that will cater for the opening of new mines or to carry out substantial exploration campaigns (Gerard , 2021). Some of the reasons for this is that the imposed requirements to investors by the South African government are high. These include regulatory uncertainty, corporate taxes, mineral royalties, formal social obligation costs, compelled and complex local procurement rules, and obligatory national ownership of at least 30% rising to 51% in some commodities (BEE, employee and community ownership), with at least part being required to be free carried at the investors' expense (Miller, *et al.*, 2021).

There are generally two types of exploration; brownfield operations which include continued exploration at existing mining operations to extend the life-of mine and greenfield operations include exploration of mineral deposits in previously unexplored areas or in areas where they are not already known to exist (Bhowan-Rajah, 2021). Although SA has not attracted exploration investments in years, there are currently a few exploration projects, which are mostly brownfields in existing mines and for the purpose of extending the life of mine. A few of these are listed in Table 7 as recommended in one of the stakeholder engagement workshops.

Table 6. A depiction of commodity contribution to employment (MCSA, 2020)

	Gold	PGM	Diamonds	Chrome	Iron ore	Manganese	Non-ferrous metals	Coal	Industrial minerals	Other minerals	Total
2009	159,926	184,162	11,601	10,966	13,728	5,003	-	70,791	13,254	22,363	**491,794**
2010	157,019	181,969	11,467	13,982	18,216	5,879	-	74,025	13,118	23,231	**498,907**
2011	144,799	194,745	12,047	16,911	22,360	7,460	-	78,580	13,013	22,961	**512,874**
2012	142,200	197,752	12,332	19,762	23,380	8,685	-	83,244	13,795	23,719	**524,869**
2013	131,738	191,260	13,579	18,358	21,127	9,842	15,539	88,039	13,623	6,805	**509,909**
2014	119,007	186,864	15,356	18,658	21,794	9,971	15,816	86,106	13,031	6,330	**492,931**
2015	115,029	186,465	18,313	18,450	20,554	8,639	16,414	77,747	12,866	5,727	**480,205**
2016	116,572	172,556	18,789	15,449	16,651	7,242	14,754	77,259	13,222	5,797	**458,291**
2017	112,901	172,760	18,038	16,968	17,510	7,780	16,325	82,372	13,029	6,219	**463,901**
2018	100,189	167,041	16,361	18,935	18,613	9,352	17,466	89,647	12,712	6,121	**456,438**
2019	**92,916**	**168,102**	**15,252**	**20,901**	**19,769**	**11,143**	**19,593**	**94,297**	**12,195**	**5,847**	**460,015**

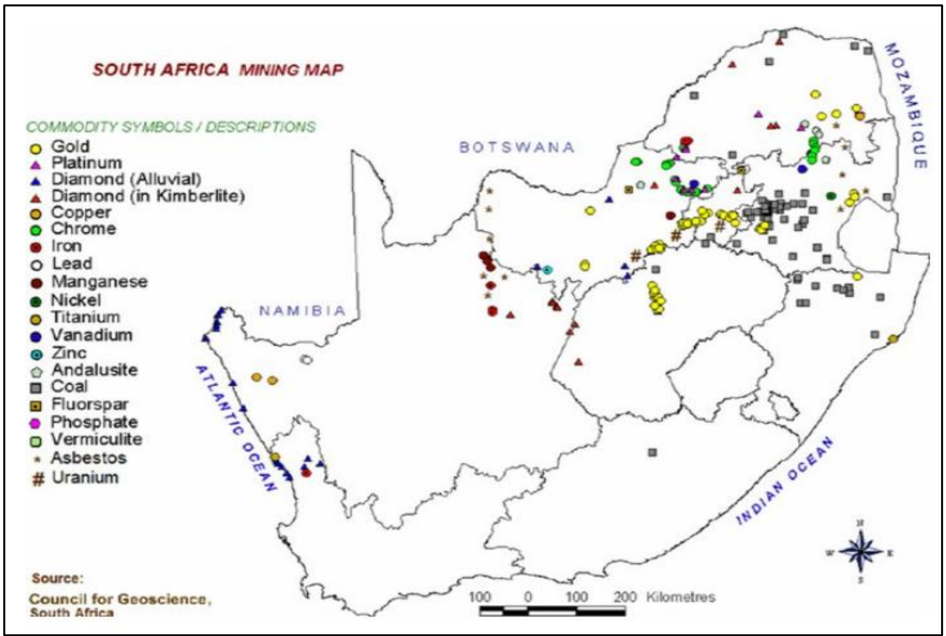

Figure 6. Minerals in SA across the nine provinces (Council for Geoscience, 2021)

Table 7: Brownfield exploration projects in some of the South African mines

Type of exploration	**Mine**	**Project name**	**Project description**
Brownfield	Harmony Gold	Kalgold expansion and prospecting rights	The expansion is focused on extension of Kalgold open-pit mining operation. The prospecting rights is aimed at increasing of the potential to develop the Kraaipan Greenstone Belt into a new mineralised province with multiple mining centres.
Brownfield	Harmony Gold	Joel - high grade Beatrix reef extension (Klippan)	The purpose is to upgrade the current mineral resource to indicated level and determine the economic mining limit in the north and north-east areas originally classified as non-depositional zones.
Brownfield	Sibanye Stillwater	Akanani project	Exploration of a delineated mineral resource that offers the potential for a long-life, low-cost operation.
Brownfield	ARM	Dwarsrivier 372 KT farm project	The purpose was for geological delineation.
Brownfield	Kumba Iron Ore	On-mine exploration	Purpose to refine the characterisation of existing Mineral Resources associated within actively mined pits and improve geological confidence of satellite deposit Mineral Resources in mining right areas that are not associated with actively mined pits.

Source: (ARM, 2021; Harmony Gold, 2021; Kumba Iron Ore, 2021; Sibanye Stillwater, 2020)

Appendix B – Economic viability of minerals and metals

The South African mining sector has a set of standards, recommendations and guidelines that is followed when reporting exploration results, mineral resources and mineral reserves (SAMCODES, 2016). The standards are known as the South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC Code). The SAMREC Code forms part of the 11 members of the International Family of International Mineral Reporting Codes (CRIRSCO). The code does not apply to resources such as oil, gas and water. Mining houses are obliged to release public reports annually to inform investors or potential investors and their advisors on exploration results, mineral resources and mineral reserves. The annual report must be prepared and signed by a Competent person. A competent person is a person with a minimum of five years relevant experience in the style of mineralisation or type of deposit under consideration and in the activity which that person is undertaking. Additionally, they should be registered with professional bodies such as South African Council for Natural and Scientific Professions (SACNASP), Engineering Council of South Africa (ECSA), South African Geomatics Council (SAGC).

The SAMREC code considers three principles with regards to public reports published by mining houses (SAMCODES, 2016):

- Materiality – A public report should contain relevant information expected and required by investors and their professional advisors for them to make reasonable judgements regarding the exploration results, mineral resources and mineral reserves being reported.
- Transparency – The public report should provide the reader with sufficient information that is clear and unambiguous to avoid misunderstanding and misleading.
- Competency – The information in the public report should be based on work conducted by a qualified and experienced competent person.

The SAMREC code applies to all solid materials required for public reporting of exploration results, mineral resources and mineral reserves. There is a framework of the SAMREC code which constitutes three categories, namely Exploration Results, Mineral Resources and Mineral Reserves (see
Figure 7).The categories move from minimum geological information, understanding and confidence to sufficient geology information and confidence to demonstrate economic viability (SAMCODES, 2016). Exploration Results is the lowest category where introductory geological work has been completed and some information on the grade, width, geophysics and geochemical of the orebody is known. The Mineral Resource category is for situations where through additional scientific and engineering work and geological modelling, the project demonstrated possible eventual economic viability. Based on the geoscientific confidence levels, the project can further be categorised as inferred (low confidence), indicated (intermediate confidence) and measured (highest confidence). The aforementioned will all still require geological and grade continuity. The Mineral Reserve category holds the highest standing. It is for situations where the project has demonstrated substantial evidence that the project is economically viable at present.

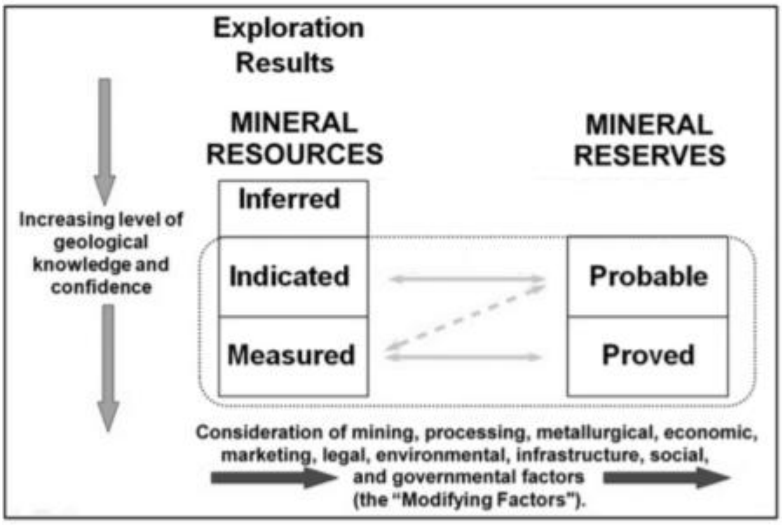

Figure 7. Relationship between exploration results, mineral resources and mineral reserves (SAMCODES, 2016)

Appendix C – Uses of locally sold minerals

This appendix links with Section 0 of the report. The uses of locally sold minerals are presented in Table 1.

Table 1. Uses of locally sold minerals

Mineral	**Uses locally**
Chrome	• Used as an alloy and in stainless and heat resisting steel products • Used in chemical and metallurgical industries
Coal	• Fuel to generate electricity • By-products from burning it are used to produce concrete • Fuel cars, ships and motorcycles when converted to gas and liquid
Copper	• Used in building construction, electric and electronic products (cables and wires, switches, plumbing, heating) • Transportation equipment • Roofing • Chemical and pharmaceutical machinery
Diamond	• Due to their hardness, they are used in saws, drill bit cuts and grinding wheels bevel in the automotive industry • Diamond membranes are used in diamond mirrors • Jewellery making
Gold	• Jewellery manufacturing, arts, dentistry, medicine, medallions and coins • Found in connectors, connecting wires, switches due to its highly efficient conductivity
Iron ore	• Steel making ingredient for local beneficiation (most important iron ore for steel is hematite (Fe_2O_3) and magnetite (Fe_3O_4) • Used in medicine, cosmetics, engineering, construction, paint
Lead	• Used in batteries • Electrical and electronic applications • TV tubes and glass • Construction • Communications • Protective coatings and weights
Manganese ore	• Used for iron and steel production
Nickel	• Stainless steel; catalyst in the hydrogenation of vegetable oils • Production of fertilisers, fungicides and pesticides
PGM	• Bushings for making glass fibers • Used in fiber-reinforced plastic and other advanced materials, in electrical contacts • Found in ethylene-removal technology created for the fresh produce industry • Used in capacitors, conductive and resistive films in electronic circuits and dental alloys • Used for making crowns and bridges
Silver	• By-product of gold, lead-zinc and copper mining, and therefore its price is also dependent on the vagaries of these metal markets •
Zinc	• To galvanise iron of steel that is used in cars, buildings and electronics

Source: (Anglo American, 2022; MCSA, 2019; NMA, 2016; RSC, 2021)

Appendix D – Defining critical raw materials

Critical minerals and strategic minerals/materials are often used interchangeably, however, some countries have varying definitions that drive the country's mineral strategies. A country's strategic/critical minerals list is updated with increasing frequency as both demand and technology evolve and are mainly driven by the transition to more green energy (Spandler, 2021). Each country has a different method for classifying certain minerals strategic or critical. For instance, China has 24 minerals listed as strategic, and that status was attained because these minerals are essential in safeguarding the economic security, defense security, and developing the needs of strategic emerging industries (Hui, 2021). In the US, critical metals are defined as minerals that are identified by the Secretary of the Interior to be a non-fuel mineral essential to the national and economic security of the US; the supply chain is vulnerable to disruption; and minerals that serve as an essential function in the manufacturing of a product, the absence of which would have significant consequences to the economy or national security (Hui, 2021). The EU defines its critical raw materials as raw materials that are economically and strategically important for the European economy but may have high risk associated with their supply (Ferro & Bonollo, 2019). The European Commission carried out a criticality assessment at the EU level on a wide range of non-energy and non-agricultural raw materials using two main parameters which are:

- Economic Importance
- Supply Risk

Economic importance is calculated using the formula below:

$$EI = \sum_{s}(A_s \times Q_s) \times SI_{EI}$$

Where:
EI = Economic Importance
A_s = The share of an end use of a raw material in a NACE Rev 2 (2-digit level) sector
Q_s= The sector's VA at the NACE Rev (2-digit level)
SI_{EI} = The substitution index of a raw material related to economic importance
S = denote sector

To calculate the supply risk, the following formula is utilised:

$$SR = HHI_{WGI} \times (1 - EoL_{RIR}) \times SI$$

Where:
HHI = is the Herfindahl Hirschman Index
WGI = is the scaled World Governance Index
IR = stands for Import Reliance
EOL_{RIR} = is the End-of-Life Recycling Input Rate
SI = Substitution Index (in supply risk)

Economic importance intends to highlight the importance of certain materials to the EU economy in terms of its end-use application and value-added to the manufacturing sector. Furthermore, supply risks show the risk of a disruption in the Eu supply of said material (European Commission, n.d.)

In Australia, critical minerals refer to minerals that are essential for the economic and industrial development of major and emerging economies (Hui, 2021). Germany classifies minerals as critical based on supply risk and vulnerability to supply restrictions of each material and further divides mineral criticality into six sections (Bendavic', 2019). In SA, the term strategic is generally accepted as critical raw materials and it refers to minerals that are of national importance whose supply is at risk (Anderson & Blake, 1984). The importance may be affected by factors such as import dependence, a limited number of significant suppliers, use in sensitive technology, and geological scarcity (Anderson & Blake, 1984). For the context of this study, the critical or strategic minerals definition that will be adopted is the global one that speaks to economic importance and supply risk and the terms strategic and critical minerals will be used interchangeably

Appendix E – Critical minerals and emerging technologies

Concerns over the availability and supply of raw materials that are essential to society's needs and especially those that have had increased demand in recent years have led to countries developing minerals strategies (British Geological Survey, 2022). The main driver for the continued demand growth for critical raw materials is the economic growth particularly in developing countries and the emergence of environmentally friendly technologies such as renewable energy and EVs. The degree or extent of criticality for any raw materials (including minerals) is reliant on the supply risk and economic importance (European Commision, 2017). Furthermore, supply risk is influenced by several factors such as geological scarcity; political stability of supplier countries; concentration of resources, production and production rate; method of recovery; and trade policies (Geoscience Australia, 2019).

Therefore, the approach adopted to determine SA's strategic minerals (at a conceptual level) was to assess the emerging technologies landscape that will drive the demand for specific minerals and metals.

An increased supply of critical raw materials is essential to the growing market of emerging technological innovations largely driven by the low carbon economy transition (The World Bank, 2017). These include technologies associated with wind, hydro and solar power. Industrialisation, technological innovations and the renewable energy transition has resulted in the rise of demand for some minerals that previously had limited importance to the economy and industry at large (Stuermer, 2014). With the national initiatives and all industries across the world embracing the 4IR by adopting new technologies and trying to achieve a low carbon future, countries are forced to take up the task of understanding minerals that are vital to their collective futures and their economies (Birol, n.d.). This will assist them in understanding the requirements to secure a reliable supply of these minerals and developing mineral strategies that will ensure sustainable development in the mining industry. Some of the emerging technologies and their associated minerals required for development and/or operations are shown in Table 2.

Several countries are progressively moving towards renewable energy sources to meet energy demands and also to reduce their carbon footprint. To meet these demands, the use of electrical motors, batteries, wind turbines, solar and hydropower is essential while it will also limit greenhouse gas emissions (GHG) (Buschke, *et al.*, 2021). With the world becoming more digital, and the development and operation of future technologies becoming increasingly dependent on these critical minerals, it is important that linkages between renewable energy, digital technologies, and the corresponding critical minerals be understood. Metals like cobalt, titanium, and platinum are essential in generating stationary power and transport using fuel cells. Furthermore, lithium-ion batteries which are efficient in EVs, portable electronics, and stationary energy are heavily reliant on the supply of cobalt, lithium, and copper (Xu, *et al.*, 2010). PGMs are used in a variety of technologies, however, catalytic convertors and autocatalysts are the largest drivers of the demand for PGM metals (Johnson, 2021). The automotive industry is the major driver for platinum demand, also more substitution of platinum for palladium has boosted demand for platinum (Creamer, 2021). Palladium is also heavily in demand as a catalytic convertor in car exhausts, although it has some use in electronics, dentistry and jewellery. Although palladium has no use in EVs and that could result in its demand decreasing drastically, it is still used in hybrid vehicles (The Economic Times, 2021). Rhodium is primarily used as a converter of automobiles, it also has uses in other industries like jewellery, alloys, and chemical industry although to a lesser extent (New Age Metals, 2020). Ruthenium and iridium are used together in multiple chemical processes, however, there is additional demand for ruthenium from the agriculture industry for use in nitrogen fertilizers (Sibanye Stillwater, 2022). Like platinum, ruthenium can potentially play a role in the hydrogen economy. In 2019, the demand for ruthenium and iridium stemmed from electrical, electrochemical, chemical auto and medical industries.

Table 2. List of emerging technologies and the corresponding minerals required

Emerging technology	Corresponding mineral required to develop the technology
Hydrogen fuel cells	Platinum, rare earth elements (REEs), PGM, cobalt, vanadium, manganese
3D printing	Titanium, magnesium, REEs, lithium,
Solar photovoltaic cells	REEs, copper, aluminium, Indium, gallium, selenium, silver, tellurium
Robotics	Cobalt, chrome, lithium, vanadium, PGM,
E-mobility	Manganese, nickel, copper, PGM vanadium, cobalt, natural graphite
Drones and unmanned aerial vehicles (UAVs)	Manganese, chromium, nickel, copper, tellurium
Cloud and remote computing	Copper, REEs, indium, tungsten
Energy storage	Copper, cobalt, nickel, lithium, REEs

Source: (Gov, 2020), (Anglo American, 2019) (LePan, 2021)

Anglo American (2019) highlighted that current trends in technology developments indicate an inevitable transition towards sustainability (Anglo American, 2019). The mining industry alone already has several technological innovations that are set to nudge the industry to more circular / sustainable mining. These include spatial data visualisation that is three dimensional (3D), virtual reality (VR), and augmented reality (AR) capabilities, geographic information systems (GIS) capabilities, artificial intelligence (AI), and automated drones. Fuel cell vehicles that utilise hydrogen as a source of fuel provide another opportunity for platinum. Since the world is transitioning to green energy, it is expected that platinum demand will increase in the coming decades (New Age Metals, 2020).

The World Bank Group reported that minerals like graphite, lithium, and cobalt would require increased production by nearly 500% by 2050 in order to meet the increasing demand for clean energy technologies (The Word Bank, 2020). To achieve the desired below 2°C and low carbon footprint, it is estimated that over 3 billion tons of minerals and metals will be consumed in installing wind, solar, geothermal power, and energy storage. The growing demand for a low carbon future is expected to result in an increased demand for several minerals and metals, including aluminium, copper, lead, lithium, manganese, nickel, silver, steel, zinc, and REEs like indium, molybdenum, and neodymium (The World Bank, 2017).

Due to its ability to be infinitely recycled, aluminium is another metal that is dubbed as a 'Metal of the future' (Kapur, 2020). REEs are another group of metals that has gained notoriety in recent years as a result of their importance in critical high technology. REEs have various uses across industries, however, most of them are utilised as a catalysts and magnets in low carbon technologies (LePan, 2021). Other applications include high-end devices, batteries, steel alloys, home appliances, aerospace, medical, internet, and radars among others (Yuksel, 2021). REEs are 17 in total namely: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc), and yttrium (Y). Technologies like clean energy, military and the consumer electronic sectors have become increasingly integrated with REEs, and the growth of these sectors automatically increases the demand for REEs (Massachusetts Institute of Technology, 2016). China is the global leader in production and reserves in REEs, accounting for 38% of the world's reserves and 140 000t in production in 2020 (LePan, 2021). Moreover, SA contains about 0.7% of the world's reserves, although no mining of REEs has taken place in SA, the reserves found are reported to be of very high-grade (Steenkampskraal, 2022).