# A review of circular economy opportunities in the mining sector

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## Abstract

**Circular economy opportunities for the mining sector are presented in this paper. A literature review was undertaken, followed by qualitative data gathering through survey questionnaires and unstructured interviews, and stakeholder engagements through workshops. The circular economy opportunities were identified and categorised according to the three circular economy principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.**

**Opportunities aligned with the first principle include increased ore extraction efficiency processes, water recovery and recycling, substitution of raw materials, technology and waste utilisation for carbon capture and biotechnology. The second principle includes opportunities such as zero waste-to-landfill strategies, repurposing of mine waste, re-mining of tailings, recycling metals and processing of residues, and urban mining of electronic waste. Opportunities aligned with the third principle include the adoption of renewable energy, green hydrogen production, repurposing of post mining landscapes, and eradication of alien invasive vegetation.**

**Furthermore, the challenges of implementing circular economy in the mining sector are discussed. The current rate of waste generation from mining activities far exceeds the rate of reuse and repurposing. Recycling of large tyres and characterisation of hazardous electronic waste also pose challenges.**

**The most implementable circular economy opportunities in the mining sector are those aligned with the second principle of keeping materials in use. The high impact opportunities aligned with the first principle of designing out waste and pollution, and the third principle of regenerating natural systems, are more difficult to implement as they require large investments.**

## Keywords

**circular economy, circular economy opportunities, mining sector, keep materials in use, design out waste, regenerate natural systems**

## Introduction

The circular economy (CE) concept has gained traction in recent years as a model for sustainable resource use, which promotes socio-economic development. A CE is defined as a systematic approach to economic development designed to benefit businesses, society, and the environment (EMF, 2017). In contrast to the linear take-make-dispose economic model, a CE promotes "keeping materials and products in circulation for as long as possible through practices such as re-use and repurposing of products, sharing of underused assets, repairing, recycling, and remanufacturing" (Schroder, 2020). The International Council on Mining and Metals (ICMM) (2023) noted that "a circular economy results from mining processes that minimise, re-use and ultimately eliminate waste, and from product design and collection processes that harvest and re-use metals indefinitely" (Figure 1).

The CE is supported by three principles, namely (DST, 2019; ACEA, 2018; ICMM, 2016):

i. Designing out waste and pollution.
ii. Keeping products and materials in use.
iii. Regenerating natural systems.

Businesses, including mining companies, are under pressure to transition to more sustainable business models to fulfil South Africa's commitment to the 2030 Agenda for sustainable development and to achieve their net-zero targets. Based on the three principles that underpin a CE, the model could

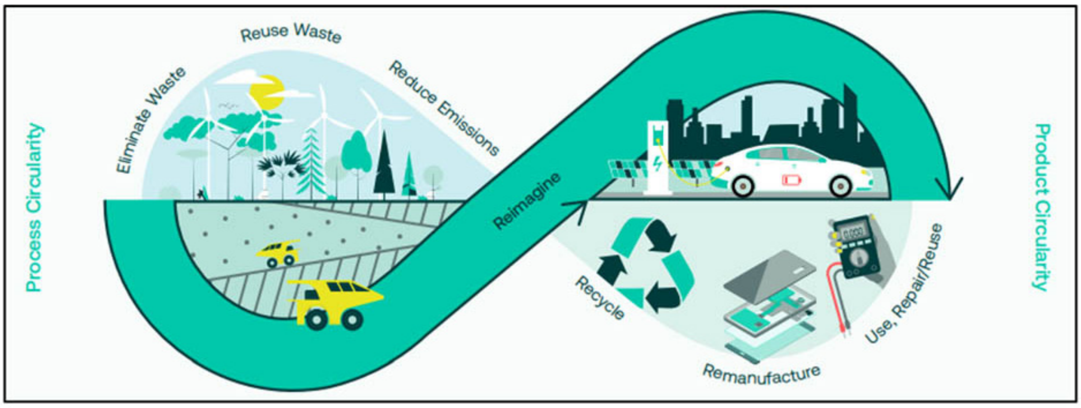


**Figure 1—Mining and metals in a circular economy (ICMM, 2023)**

potentially support this transition by designing out waste and pollution from business/mining processes, keeping products and materials in use for as long as possible, and regenerating natural systems (Suchek et al., 2021; DST, 2019; ACEA, 2018; ICMM, 2016).

The objective of this paper is to provide a high-level overview of some of the CE opportunities for the South African mining sector as well as the associated challenges. The contents of this paper have been extracted from a study done by Khan et al. (2021), detailed in a report titled: *South Africa's mineral resource availability as a driver for transitioning to a Circular Economy.*

The study was funded by the Department of Science and Innovation through the Waste Research Development and Innovation (RDI) Roadmap Implementation Unit hosted by the Council for Scientific and Industrial Research (CSIR).

## Methodology

A desktop study was undertaken to understand the relevance of a CE in the mining sector, after which a briefing note titled: *Placing the South African mining sector in the context of a circular economy transition*, was published. The briefing note was used to initiate discussions with stakeholders on CE opportunities within the mining sector.

This was followed by a literature review, and the gathering of qualitative data through survey questionnaires, unstructured interviews with subject matter experts, and workshops with key stakeholders. Stakeholder engagements were conducted through two workshops and interviews between January 2022 and February 2022. The stakeholder groups for the first workshop included geologists, mining engineers, mineral economists, and mineral resource management practitioners. The stakeholder groups for the second workshop included environmental management practitioners, professionals involved in issues related to sustainability, environmental, social, and governance (ESG), and materials stewardship.

The information solicited enabled the project team to determine the CE opportunities as well as the associated challenges for the mining sector.

## CE opportunities for the mining sector

Based on the study undertaken, some of the CE opportunities in the mining sector have been identified and categorised according to the three CE principles.

Table 1 presents a summary of the CE opportunities in the mining sector.

*Table 1*

**Summary of circular economy opportunities in the mining sector**

| CE principle | CE opportunities in the mining sector |
|---|---|
| i. Design out waste and pollution. | • Increased ore extraction efficiency and precision. |
| | • Water recovery and recycling. |
| | • Substitution of raw materials. |
| | • Technology and waste utilisation for carbon capture. |
| | • Biotechnology or biomimicry. |
| ii. Keep products and materials in use. | • Reusing, reducing, and recycling of waste. |
| | • Processing of residues and secondary metals. |
| | • Re-mining of tailings and waste. |
| | • Zero waste-to-landfil strategies. |
| | • Urban mining of electronic waste (e-waste). |
| iii. Regenerate natural systems. | • Integration of renewable energy in mining operations. |
| | • Green hydrogen generation. |
| | • Repurposing of post-mining landscapes. |
| | • Eradication of alien invasive plants for water reutilisation. |

The CE opportunities for the mining sector are discussed in the following subsections.

### *Design out waste and pollution*

#### *Increased ore extraction efficiency and precision*

The generation of waste and pollution could be minimised through the development of technologies that could enhance precision and efficiency of ore extraction, with minimal energy usage, reduced water, and capital intensity. Examples of these processes include coarse particle recovery, bulk sorting, ultrafine recovery, fracking, and in situ mining (Anglo American, n.d.).

Kumba Iron Ore, on their journey to sustainable mining, implemented the ultra-high dense medium separation technology, which improved their beneficiation by essentially converting their previous 'waste' into ore. The technology also extended Sishen mine's life from 12 years to 19 years (Creamer, 2021). The Minerals Council South Africa (2019), suggested that modernisation of the mining sector could enable viable extraction of lower-grade orebodies and deeper resources, which cannot be economically mined using current technologies. Modernisation of the mining industry presents an opportunity to reduce the sterilisation of mineral resources, ensuring that the sector derives maximum benefit from the mineral commodities. Thus, modernisation will extend the life of mines (minimise premature mine closures) and enable the development of new low-grade deposit operations. This will subsequently preserve jobs and create new employment opportunities in the mining sector.

Other ways to increase efficiency and precision is to address current issues such as poor fragmentation and excessive ore dilution due to poor drilling and blasting (Pysmenniy et al., 2020). Efficient ore extraction could potentially extend the life of mining operations and increase the range of mineral recovery. This could reduce the environmental footprint as the need to develop greenfield mines will decrease.

#### *Water recovery and recycling*

Water scarcity and poor water quality is a major crisis in South Africa (SA), resulting from overexploitation of water resources, lack of infrastructure maintenance, ineffective water resource management, and climate change, which consequently impacts food production (Donnenfeld et al.; 2018; National Planning Commission, 2012). To improve the ecological system, dependence of the mining sector on fresh water sources should be reduced and uptake of water recovery and recycling processes should increase. Possible innovative technologies for water recovery and recycling include dry processing, evaporation management, novel leaching, and dry stacking (Anglo American, n.d.). Implementation of these technologies could enable mines to transition from wet tailings storage facilities, which pose serious failure hazards, to dry stacked tailings, thereby creating stable and sustainable land.

#### *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 (SGS Mineral Services, 2008).

The European Commission has developed a raw materials commitment, which seeks to identify and develop sustainable substitutes for critical raw materials (CRM) in various industries, including mining (European Commission, 2019). This suggests that substitution of raw materials could assist in meeting the global demand for CRM for development of clean energy technologies.

#### *Utilisation of captured carbon for value-added products*

With the advancements in carbon capture technologies, there is potential to convert carbon dioxide ($CO_2$) into value-added products. These products include clean fuels and chemicals such as methanol, formic acid, and acetal through thermocatalytic, electrochemical, photocatalytic, microbial, and enzymatic methods. Other industrial applications of $CO_2$ from carbon capture are the production of organic carbonates and polycarbonates, which are used in lithium-ion batteries and pharmaceuticals, and conversion of $CO_2$ into supercritical fluids, which are beneficial in chemical processes (Podder et al., 2023).

#### *Biotechnology or biomimicry*

Biotechnology may be used to tackle e-waste, which is one of the fastest growing categories of waste (Xavier et al., 2021), e.g., by recovering metals from appliances, cellphones, etc. Biohydrometallurgical processes are the most feasible for urban biomining and include methods such as bioleaching, bio-oxidation, and biosorption (Xavier et al., 2021).

Kumba Iron Ore's zero waste-to-landfil strategy incorporates bioremediation of hydrocarbon contaminated soils using bacteria. The bioremediated soil can then be used for rehabilitation of land, instead of being disposed as hazardous material in landfill sites. From the data gathered, it was also found that biomimicry should be considered as a sustainable solution for managing waste as there is a fungus or a bacterium for any type of man-made pollution. It has not really been explored to the extent that is possible or that we should. They are nature's solutions.

Minerals and metals such as nickel can also be extracted using plants that have been enhanced through synthetic biological processes specifically for this function. The plants are grown in nickel-rich soil and then harvested, following which the metal is recovered from the biomass. This process enables the extraction of minerals in soil below traditional cut-off grades (Genomines, 2022). This innovative extraction process could potentially contribute to closing the supply gap for critical raw materials by using more sustainable and environment-friendly methods of mineral extraction.

### *Keep products and materials in use*

The keep materials in use principle has widely been adopted across the South African mining industry. The interventions under this principle include reducing, reusing, and the recycling of various waste streams, including end-of-life equipment. Some of the CE opportunities under this principle are briefly discussed in the section that follows here.

#### *Zero waste-to-landfill strategies*

The zero waste-to-landfill strategy is a waste management approach, which aims to divert at least 99 per cent (99%) of all waste generated at a particular business away from landfils (Carbon Trust, 2017; Intertek, n.d.). This implies that all waste that is produced will be either reused, recycled, composted, or sent to energy recovery. As reported in their 2020 sustainability report, Anglo American's Kumba Iron Ore adopted the zero-waste-to-landfil strategy that was aimed at eradicating waste disposal in landfills (Anglo American, 2020).

*Reuse/repurposing of mine waste*

CE interventions under the reuse and repurposing of mine waste principle include (Lottermoser, 2011; ICMM, 2016):

- ➤ Repurposing waste rock for several uses such as reprocessing to extract remnants of valuable minerals, buttressing of highwalls, landscaping, aggregates for construction, raw material for cement manufacturing, and backfilling mined-out areas.
- ➤ Using manganese tailings for producing resin, glass, construction materials and coatings, and in agroforestry.
- ➤ Using clay-rich tailings for bricks, cement, and floor tiles manufacturing.
- ➤ Utilising slag in road construction, and cement and concrete production.
- ➤ Repurposing bauxite red mud for soil and wastewater treatment, and as a raw material for ceramics, glass, and brick manufacturing.
- ➤ Reusing mine water for several purposes such as cooling, source of drinking water, dust suppression, and mineral processing, and for other agricultural and industrial applications.
- ➤ Making pigments using iron-rich sludge from acid rock drainage treatment.
- ➤ The repurposing of old tyres is another CE opportunity, which has been adopted by some mines locally and globally. Thermal conversation/pyrolysis of tyres (a process in which the organic material in tyres is decomposed with heat in the absence of oxygen, thus converting the tyres back into their original components, namely fuel oil, carbon black, and steel) could potentially provide a sustainable solution for recycling large tyres towards a circular economy (Kal Tire, 2023). For example, a 63-inch diameter radial tyre could be broken down using thermal conversion/pyrolysis to produce approximately 1600 kg of carbon ash, 900 kg of high tensile steel, 2000 litres of petroleum-based products, and 350 cubic metres of synthetic gas (Figure 2). The carbon ash can be used as a replacement for new carbon black, while the petroleum-based products can be used to create new tyres and the synthetic gas that is used to feed the recycling process (Kal Tire, 2023).

*Re-mining of tailings*

Mining companies are leveraging on technological developments and innovations to re-mine tailings. Re-mining of tailings gives the mining industry an opportunity to convert legacy mining-related liabilities into opportunities, which can create alternative economic and employment opportunities. For example, Sibanye-Stillwater successfully implemented the West Rand Tailings Retreatment Project (WRTRP), resulting in the realisation of some shared benefits to all key stakeholders (Sibanye Gold, 2016). Other South African mining companies involved in re-mining of gold waste rock dumps include DRDGOLD, Mintail, and Goldfields.

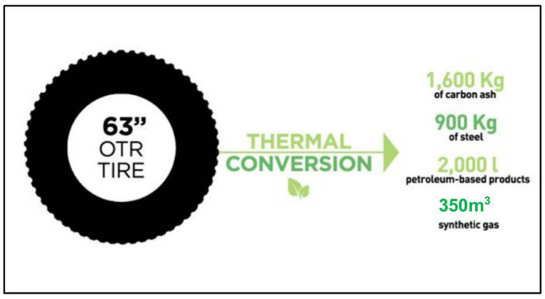


**Figure 2—Thermal conversion/pyrolysis of large tyres (Kal Tire, 2023)**

*Recycling metals and processing of residues and secondary metals*

Under this initiative, new scrap is directly remelted to new metal or melted and refined to pure metal or alloys with limited oxidation and reduction, while old scrap and metal containing wastes or residues are usually refined via pyro-, hydro-, and electrometallurgical techniques.The aluminium industry is embracing the recycling of scrap metal, which was accelerated by the COVID-19 pandemic-related logistics challenges associated with bauxite imports. Aluminium is a potential 'green' metal that can be recycled several times without losing its original properties (European Aluminium, n.d.).

Besides the efforts aimed at reducing waste generated from mineral processing-related activities, additional CE opportunities can be harnessed from the processing of secondary metals and residues. Practical CE opportunities under this thrust area include (ICMM, 2016):

- ➤ Producing metals using scrap in combination with primary concentrates.
- ➤ Producing valuable metals such as gold, silver, copper, and palladium from secondary smelting of electronic scrap.
- ➤ Enhancing the recovery of coproducts from mining activities. For example, a nickel mining company can opimise the recovery of coproducts such as copper, platinum-group metals (PGM), and cobalt.
- ➤ Decreasing the volume of acid gases emitted into the natural environment by interventions such as producing sulphuric acid using the off-gas cleaning process in primary smelters.
- ➤ Converting sulphur dioxide to sulphuric acid through processes such as the incorporation of acid plants into the smelting process.

*Urban mining of e-waste*

There is an opportunity for existing mining companies to create alternative business models and employment opportunities through the recovery of end-of-life products and/or e-waste (urban mining). Mining companies can create subsidiary companies that recover and reprocess scrap metal. It was reported that since 2018, less than 10% of e-waste was collected for recycling in SA and most of the e-waste was exported and processed internationally. It is noteworthy that the University of Cape Town commissioned a research project aimed at developing technologies to recover and process copper and gold from circuit boards in SA. The project will also investigate the feasibility of using the chemical extraction process for copper using ammonium sulphate (Eco Africa, 2021).

***Regenerate natural systems***

*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 South Deep mine near Westonaria constructed its 50MW Khanyisa solar plant to partially mitigate the impacts of Eskom's unreliable supply

(Gold Fields, 2022). Gold Fields (2022) reported that the solar plant saves 24% of their electricity costs and can also significantly reduce their carbon emissions.

### *Green hydrogen generation*

Green hydrogen production has huge economic potential for SA, which would consequently result in increasing demands for PGM - 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 electric vehicles (EV). 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 SA 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 abundant in SA. This positions SA favourably and has potential for its economy in the future - decarbonisation of its local economy and exporter of green energy (PwC, n.d.).

### *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.

### *Eradication of alien invasive plants for water reutilisation*

SA's Working for Water (WfW) programme aims to accelerate the eradication of invasive biomass. It is said that 2.9% to 6% of water is captured by alien invasive plants – when removed, water may be released for other uses (Department of Forestry, Fisheries and the Environment, 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.

## Challenges to the implementation of circular practices

The study found that several CE opportunities are available and already being implemented in a silo fashion across the industry. However, the holistic and sustainable adoption of circularity across the mining sector continues to face several challenges. Huge volumes of waste rock and tailings are generated from mining activities. However, the current rate of reuse and repurposing is much lower than the rate at which the waste is generated.

Anglo American (2020), reported that their zero-waste-to-landfill strategy faced a challenge in the segregation of non-hazardous waste because not all waste streams could be recycled due to technological constraints. There is a general lack of sustainable solutions to recycle large tyres, which are difficult to handle and manage. Anglo American (2020) further noted that Kumba Iron Ore stored about 20 000 tonnes of scrap tyres in 2020 and the company was still exploring circular economy solutions for the management of large waste tyres.

The study revealed that although some of the aforementioned CE interventions are economically viable; they are not always operationally feasible to implement. For example, backfilling of mined-out areas using waste rock could be difficult to implement in surface mines practicing selective mining and blending of ore from different areas within the pit at different times, in order to meet the required quantities and quality of ore. There is a need for collaborative research, development, and innovation (RDI) to develop innovative and implementable CE interventions to address these waste management challenges.

The research established that although pockets of CE interventions have been adopted across the mining sector, the adoption has not been done holistically and, at a large scale, results in marginal realisation of the socio-economic and environmental benefits. It is envisaged that a holistic adoption and large-scale implementation of CE interventions across the mining sector could offer the industry an opportunity to convert legacy waste management issues into significant socio-economic opportunities.

ACEA (2018) argued that the large-scale roll-out of CE solutions in the mining sector could be inhibited by huge investment requirements associated with the interventions. The study found that sustainable circularisation of the mining industry requires a collaborative approach among all key stakeholders and the process should be underpinned by customised incentives and legislative framework.

Moreover, the research revealed that sustainable implementation of longer-term CE opportunities such as urban mining of e-waste could be hindered by difficulties related to hazardous e-waste characterisation. Thus, there is a need for further RDI to develop solutions to some of these challenges.

## Conclusion and recommendations

The most implementable CE opportunities in the mining sector are those aligned with the keep materials in use principle and many mining companies are already implementing practices aligned with this second 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 the implementation of these initiatives. The challenges are mainly operational and financial, suggesting that RDI are key focus areas to addressing these issues.

The high impact opportunities aligned with the first principle of designing out waste and pollution and the third principle of regenerating natural systems are more difficult to implement, as they require large investments.

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 CE principles, the interventions need to be scaled up to make a meaningful impact on the business, society, environment, and the economy at large.

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