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Review article

Towards sustainable metal extraction: Navigating energy and water challenges in the South African mining industry

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ABSTRACT

The move towards technological advancements and industrial developments such as energy transition suggests that the mining industry will need to provide the world with vast quantities of critical metals in the future. As such, the mining sector is receiving increasing attention for the role it plays as a supplier of materials necessary to build the infrastructure for a carbon neutral future. However, the mining industry continues to face a number of obstacles which might make meeting the demand for these critical metals challenging. The increasing energy demand, the scarcity of fresh water supply and the growing need for responsible mining with regards to the environment and the society, are some of these challenges. This paper highlights the challenges around water and energy utilisation in the South African metal extraction industry and further discusses some of the strategies and initiatives being undertaken by the sector in order to ensure sustainability. The paper highlights that a move from linear to a circular approach in water utilisation and the integration of renewable energy sources to support the traditional coal powered energy supplies are some of the strategies that the mining industry is initiating to safeguard the uninterrupted supply of raw materials and products in not only an economically viable way but also in a responsible manner.

1. Introduction

Metals are the backbone of societies and are essential in the development of technologies that drive global economies. The world's dependency on metals has become more evident with the growing demand for critical metals required to drive advancements in the technological landscape and the energy transition. Metals will be at the centre of decarbonization efforts and electrification of the economy as we move from fossil fuels to renewable energy technologies, battery and fuel-cell-based electric vehicles (EVs) and green hydrogen production. This technological advancement continues to drive demand for metals. For instance, demand for platinum, which is one of the crucial metals for the green energy transition, will surge by 240 times by 2050 (Zhang et al., 2024). Additionally, copper demand is expected to increase by up to 3.5 times the current level by 2050 (Anani et al., 2025). Demand for other critical metals is also expected to skyrocket by 2050, indicating that the metal supply chain must be improved to meet future demand. Simply put, metals have become the new oil in the drive towards net-zero emissions. However, it is important to note that before metals can be used in all these technological applications and modern-day advancements, they must be extracted from the host resources through mining and mineral processing activities. As the supplier to the economy, the mining sector will therefore need to grow at a very fast pace to facilitate the necessary technological shifts. In general, the metal value chain involves stages such as mining to extract the mineral containing ore from the rock, ore dressing or beneficiation to concentrate the metal content in the minerals and lastly, the final metal extraction and recovery processes to obtain the solid value metal for sale to the downstream value adding processors and manufacturers.

While it is acknowledged that the modern and future world cannot function without metals, the extractive metallurgy sector has, however, not been without its challenges. The depletion of high grade and easy-to-process ores, the difficulties faced in finding new natural resources, the increasing operational costs associated with increasing energy requirements for mining at depth and the complexities faced with the beneficiation and processing of largely complex and refractory ores are some of the challenges faced by the modern mining sector. Furthermore, energy and water are two other critical inputs for metal extraction and

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recovery. South Africa is known to be a water-scarce country and among the 30 driest countries globally, with an estimated 17 % water demand higher than supply by 2030 (Seetal et al., 2023). The country hosts about 70 % of the world's platinum resources, including other mineral deposits located in water-stressed regions such as the Northern Cape. Coupled with this, the country has been increasingly facing massive challenges with regard to a stable energy supply. Between 2017 and 2022, the energy availability factor (EAF), the percentage difference between the maximum available energy and the unavailable one, decreased by 20 %, and the country continued to face an energy crisis due to ageing generating facilities (Msimango et al., 2023). Such challenges will ultimately have a long-term impact on the viability of the mining and metal extraction industry unless the industry implements radical changes. In addition to the above, communities have a negative perception of mining and have become increasingly vocal when it comes to the impact of mining activities on the environment (Seloa and Ngole-Jeme, 2022). Thus, mining companies have started to realise that while profitability might be important, metal extraction, however, should not be done in a way that would disadvantage the lives of the current and future generations. Such issues, together with global agendas such as the United Nations Sustainable Development Goals (SDGs) and the Environmental, Social, and Governance (ESG), have thus, become the drivers for change through, for example, using more holistic and integrated approaches to metal extraction and recovery techniques as well as increasing process efficiencies.

Despite these challenges faced by the mining industry in South Africa, there are limited studies with a focus on addressing the multidimensional sustainability issues. The socio-environmental impact of South Africa's mining and conflict resolution between the host communities and the mining industry in Africa can be found in the literature (Leonard, 2024). The issue of water scarcity in South Africa has been presented in the literature (Mnguni, 2020). The author, however, does not address the water challenges in the South Africa mining industry. Recent research presented potential water management approaches for improved water availability in South Africa (Olley et al., 2024). Water quality in the mining industry was discussed in terms of acid mine drainage (AMD) and other water body contamination due to mineral processing (Olley et al., 2024). The strategy to improve water management in the mining industry has not been well presented, despite that mines are in remote locations where access to water is a challenge. Likewise, information is limited as per sustainable energy use for the South Africa mining industry. A keyword search on the Scopus database using the search term "“Energy management" OR "energy efficiency" AND mine AND "south Africa"" provides no relevant documents (access date: May 18, 2025). The 36 available documents are related to energy efficiency in specific mine operations or the deployment of new technology or models for improved energy use. This paper highlights the vital role of water and energy in mining, more importantly their criticality as inputs and implications for sustainability in the South African metal extraction industry. By examining current practices, potential innovations, and the challenges faced by the industry, this paper aims to shed light on how effective strategies and approaches to the management and use of these resources can promote a more sustainable and resilient future for South Africa's mining sector. While the paper particularly focuses on the South African minerals industry, it must be highlighted that the challenges underlined herein, tend to reflect those faced by the global mining sector. Therefore, some examples from the global mining sector are also incorporated into the discussion.

2. The mineral extraction and metal recovery value chain

The primary production of metals traditionally involves their extraction from minerals that occur in the form of native, oxides, sulphides, sulphates, silicates, carbonates and hydroxides. These valuable metal containing minerals tend to be found associated with other gangue minerals and thus, have to be selectively extracted and recovered. The value chain therefore, includes mining, ore beneficiation and metal recovery (Fig. 1). The final recovery of valuable metals from ores and concentrates generally involves the application of either pyrometallurgical or hydrometallurgical processing flowsheets. However, metal extraction can also involve the integration of both techniques such as in the production of alumina, platinum group metals (PGMs) or gold. While pyrometallurgical processes employ relatively high temperatures to extract and recover the metals, hydrometallurgical processes however, tend to work under much more ambient temperature conditions in aqueous solutions.

Pyrometallurgy predates hydrometallurgy and has been used as a key technology for the extraction of metals such as copper from sulphide minerals and for the processing of alumina to produce aluminium. The technology tends to focus on two key approaches of roasting and smelting. For example, a copper sulphide ore might be roasted to create an oxide or smelted to produce a matte that can then be converted to generate a crude metallic product (Schlesinger et al., 2021). In aluminium production, on the other hand, alumina produced through the hydrometallurgical Bayer process is smelted using the Hall-Heroult process to produce pure aluminium (Ratvik et al., 2022).

As a technology, hydrometallurgy on the other hand has been applied in the mining industry for centuries with the first recorded application involving the use of aqua regia to extract metals (Habashi, 2005). Hydrometallurgy is concerned with the extraction of metals from various metal-rich feed materials such as ores, concentrates and, more recently, secondary waste streams such as e-waste, metallurgical waste etc., using water-based techniques, hence the term hydro. The process, however, involves several integrated steps that work together to promote the production of high-quality and high-grade metals (Ndlovu et al., 2017). Such unit steps include leaching to extract the metal from the feed material and getting it into solution. This step is then followed by the purification and solution enrichment step/steps to increase the concentration of the target metals, by separating them from impurities. The unit processes that can be used during this stage include for example, solvent extraction, precipitation, resin in pulp and crystallisation. The final step is the recovery of the solid metal or metal compound in its high purity state. Processes that are used in this last stage include precipitation, gaseous reduction, crystallisation, and electrowinning. Precipitation and gaseous reduction tend to generate metallic or powders of metallic compound. Crystallisation generates crystalline products whilst electrowinning generates solid metal products.

By considering the generic metal production circuit shown in Fig. 1, a number of key issues become apparent. Firstly, water is a key component in the mining and metal extraction process. Without water, it is difficult to recover most of the metals that contribute to the development of the South African economy such as gold, platinum group metals, manganese, vanadium etc. In hydrometallurgy for example, processes are all solution based and thus the use of water is a key part of the metal extraction value chain. In pyrometallurgy, water is used mostly for cooling. The second key point is that energy plays a critical role in the metal value chain, particularly during the early stages of mineral processing. Energy is essential for primary beneficiation processes, which occur before the material enters the pyro- or hydrometallurgical extraction circuits. These beneficiation steps are crucial because they improve the suitability of the feed material for downstream extraction. Beneficiation techniques work by upgrading the metal content through the removal or reduction of gangue (unwanted material), thereby reducing the volume that must be handled and processed in later stages, ultimately lowering operational costs. In addition, these techniques help reduce particle size and liberate valuable metals, which enhances the efficiency and kinetics of the extraction process. However, many of these techniques, particularly comminution (crushing and grinding), are extremely energy-intensive. In fact, comminution alone accounts for approximately 53 % of total energy consumption in mining, contributing to at least 10 % of total production costs (Jeswiet and Szekeres, 2016). Furthermore, this process accounts for 3 % of the total amount of

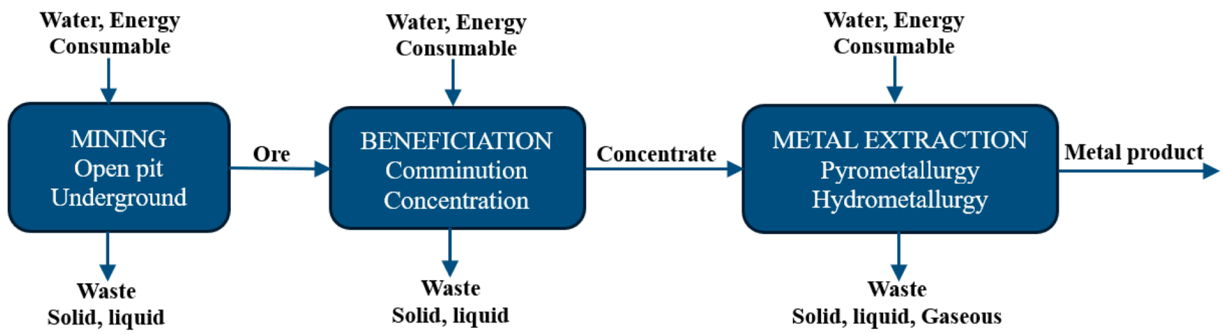

Fig. 1. Generic metal extraction process flowsheet.

electrical energy consumed globally.

After undergoing beneficiation, the material is directed to the metal extraction stage, which may involve either pyrometallurgical or hydrometallurgical processes. Pyrometallurgy, by definition, relies on high temperatures to extract and recover metals, making it inherently energy intensive. Furnaces in these processes often operate at temperatures exceeding 1000 °C to achieve effective metal separation. In contrast, hydrometallurgy typically operates at or near ambient temperatures. However, it still requires substantial energy input, for heating solutions, mixing reagents, pumping slurries, and, importantly, producing solid metals through electrometallurgical techniques such as electro-winning or electrorefining.

A final and critical point is that metal extraction processes, whether hydrometallurgical or pyrometallurgical, inherently generate two output streams at nearly every stage of the circuit: a valuable product and a waste stream (Fig. 1). These waste streams can be solid, liquid, or gaseous, and are produced throughout various stages such as beneficiation, roasting, smelting, leaching, solution purification, and final metal recovery. The nature and quantity of waste depend largely on the type and quality of the feed material. Today's mining operations are increasingly reliant on low-grade and complex ores, which require extensive pre-processing and upgrading before metals can be effectively extracted. This, in turn, leads to the generation of significant volumes of waste.

In pyrometallurgical processing, the main solid waste is known as slag, while in hydrometallurgy, it is referred to as residue or tailings. Liquid waste typically contains chemicals leftover or generated during extraction, while gaseous emissions vary based on the ore composition and any input gases used in the process. One of the most pressing challenges facing the mining industry today is tailings management. Tailings occupy large land areas and contribute significantly to environmental degradation. For example, by 1995 in South Africa, gold and uranium tailings alone had already covered over 400 km^2 of surface area (Adewuyi et al., 2024).

Generally, the more complex the feed material, the greater the number of processing steps required, leading to increased water and energy consumption, and higher waste generation. Traditionally, solid waste has been disposed of in dedicated tailings facilities, following a linear processing model, where metal is extracted and all residuals are discarded. However, this linear approach is becoming increasingly unsustainable, especially in African mining contexts, where freshwater scarcity, energy shortages, and rising power costs pose serious constraints. Moreover, this model is marked by inefficiencies in water and energy use, and an unsustainable burden of waste, making the case for a more circular and resource-efficient approach to mineral processing ever more urgent.

3. Sustainability in the metal extraction industry

While the mining industry has contributed to global economic growth for centuries, supplying metals that have powered technological progress, it has largely operated under a linear economic model (Fig. 2). This traditional metal value chain follows a straightforward path: resource extraction, metal production, consumption, and disposal, a "produce–use–discard" system that has dominated mining practices over the past century. This model has resulted in the accumulation of vast amounts of waste, including tailings (as discussed in Section 2), metallurgical residues, and end-of-life products such as electronic waste. Moreover, it reflects a limited focus on the efficient use of critical inputs like water and energy, which are essential to metal production. Underlying this approach is the flawed assumption that the Earth has an infinite capacity to regenerate its natural resources and absorb waste (Rankin, 2011). As a result, the model is increasingly seen as unsustainable, particularly in the face of growing resource scarcity, environmental concerns, and the need for more resilient supply chains.

The rising global demand for metals, combined with growing water scarcity and persistent energy supply challenges, especially across sub-Saharan Africa, underscore the unsustainability of the current linear approach to mineral extraction. To ensure a stable and secure supply of raw materials and finished products, the mining industry must shift toward practices that are not only economically viable but also environmentally and socially responsible. This shift aligns with the principles of sustainable development, which call for meeting present needs without compromising the ability of future generations to meet theirs. As defined in the Brundtland Report (Brundtland, 1987), sustainable development emphasizes the need for continued industrial and economic progress, but at a pace and in a manner that safeguards long-term ecological and human well-being.

The three pillars that form the concept of sustainable development involve social equity, economic viability and environmental protection. These can also be broken down to focus on three issues, people, profit and planet. Economic sustainability is not only about increasing profits, but also focuses more on practices that support long-term economic growth without negatively impacting social, environmental, and cultural aspects of the community. On the other hand, environmental sustainability focuses on the protection and conservation of the environment for future generations. Mineral and metal extraction companies that incorporate the environmentally sustainable pillar into their production value chain take steps to enhance process efficiencies, reduce resource consumption, reduce impact on nature and increase product or service value across the entire chain. Their key departure point is based on the fact that society must not compromise its ability to meet the essential needs of its people in the future by overexploiting resources in the now. The focus, therefore, tends to shift towards eco-efficiency i.e., doing more with less. Lastly, social sustainability, while itself very broad, can be defined in simple terms to include important workplace and employee issues like health and safety, inclusion, empowerment, and professional development opportunities, which in turn improves resource efficiency.

Success in the mining industry is increasingly being measured not just by the quantity of resources extracted, be it ounces, carats, or tons, but by the positive impact operations have on people's lives (Cutifani

Fig. 2. Linear economic model.

and Bryant, 2015). While the primary goal for most mining companies is long-term economic growth, this objective should not conflict with the principles of sustainable development. When implemented effectively, sustainability practices can support both profitability and broader societal and environmental well-being. Companies that embrace the three pillars of sustainable development, economic growth, social equity, and environmental protection, focus on creating value that benefits both current and future generations. Achieving this requires a deliberate effort to balance business success with community needs and environmental stewardship, particularly in regions affected by mining activities.

Sustainability is no longer optional; it has become central to the development strategies of economies worldwide. It forms the backbone of global frameworks such as the United Nations Sustainable Development Goals (UNSDGs) (United Nations, 2015), the African Union's Agenda 2063 (African Union Agenda 2025), and is deeply embedded in ESG standards. Within the minerals and mining sector, key sustainability priorities include water management, affordable and clean energy, responsible consumption and production, and inclusive economic growth. It is therefore evident that the long-term success of mining operations is inseparable from their ability to address these sustainability concerns. The UNSDGs have prompted both investors and industry leaders to adopt a "sustainable systems approach," recognizing that this path not only supports global development goals but also delivers significant operational benefits, such as improved efficiency, stronger community relations, and greater regulatory alignment.

This shift in thinking toward sustainability also opens new avenues for addressing the industry's most pressing challenges. One of the key strategies mining companies are adopting is a transition from traditional linear or "open-loop" operational models to more regenerative, circular models. This transformation supports sustainable development by promoting resource efficiency and minimizing waste. A circular economy approach to mining and metals production, illustrated in Fig. 3, emphasizes the reuse, recycling, reprocessing, and remanufacturing of industrial metal products and by-products. For example, mining waste can be repurposed within the mining industry itself or used in construction applications, reducing the need for virgin materials and decreasing environmental impact.

The circular economy is grounded in three foundational principles: reducing or eliminating waste, circulating products and materials through reuse and recycling, and regenerating natural systems. While various definitions exist in the literature (Kirchherr et al., 2017), they all converge on the central idea of maintaining resources in use for as long as possible, extracting maximum value during their lifecycle, then recovering and reintegrating them into the system to build economic, environmental, and social capital. Adopting such circular models not only aligns with the broader sustainability agendas outlined in the UNSDGs and ESG frameworks, but also represents a strategic move toward long-term resilience and value creation in the minerals industry.

It is, therefore, not surprising that the circular economy model is closely tied to the transition toward renewable energy and sustainable materials, as it aims to decouple economic growth from the consumption of finite natural resources. While this model clearly aligns with the economic and environmental pillars of sustainable development, its connection to the social pillar is often less explicit. However, by placing people and the planet at the heart of development strategies, the circular economy can play a vital role in advancing the UNSDGs.

Despite its promise, the mining and minerals extraction industry faces significant challenges in supporting a global shift to a low-carbon future. As demand for metal products continues to rise, driven by clean energy technologies and digital infrastructure, the industry must increase production, which in turn escalates the consumption of key inputs like water and energy. Balancing this growing demand with the principles of sustainability remains a critical priority. The continued use of natural resources must therefore, be underpinned by policies that promote long-term sustainability and intergenerational equity. If not managed responsibly, current patterns of resource consumption may

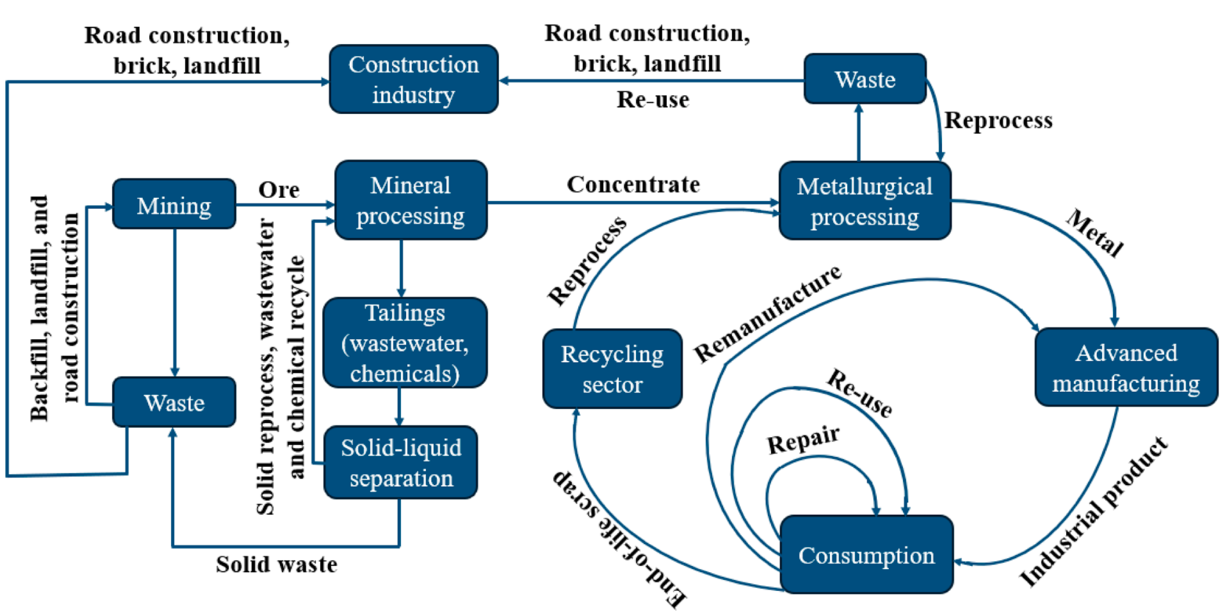

Fig. 3. Circular economy concept for metals and mining wastes.

compromise the ability of future generations to meet their own needs. Section 4 examines water and energy as strategic inputs in the mineral extraction value chain, highlighting challenges, emerging opportunities, and industry practices that are shaping a more sustainable and resilient mining sector. This discussion is especially relevant in the context of the global shift toward green energy economies, where the demand for critical minerals must be balanced with responsible resource governance.

4. Water

While the activity of ore excavation during the mining stage itself does not use a lot of water, large quantities are however, used during the mineral processing and metal extraction stages for activities such as the transportation of ores and waste slurries, physical and chemical processes, cooling systems and, suppression of dust, potable and hygiene needs. Water is used in the beneficiation stages, for example, during flotation and gravity separation operations. In pyrometallurgical processes, water is used for cooling, granulation of slag and scribing of smelter gases as well as in the acid plant. By the nature of the chemical processes that take place in aqueous media, hydrometallurgical process units use the bulk of the water. This is because water acts as a very efficient and essential medium for supplying and mixing chemicals and materials.

The direct consumption of water at a mine operation consisting of mining and a beneficiation plant can range between 0.34–6.27 m^3 per tonne of ore processed, depending on ore type, ore grade, and complexity in processing (Falconi et al., 2023). If the mining operation includes a pyrometallurgical and hydrometallurgical plant, the water usage will be in most cases 2 to 5 times higher (Rankin, 2011).

Although South Africa occasionally experiences periods of heavy rainfall and even flooding, it is fundamentally a water-scarce country, located in an arid to semi-arid climatic zone. The country's mean annual precipitation is approximately 497 mm/year, which is nearly 50 % lower than the global average of 860 mm/year (Schneider et al., 2014). This limited rainfall, combined with growing demand across sectors, places substantial pressure on water resources.

Within this context, the mining sector, while contributing only about 2–5 % of South Africa's total water consumption (Brown, 2003), remains a strategic water user, particularly in mineral processing operations that involve intensive water use. For example, research indicates that platinum group metals (PGM) production is among the most water-demanding processes in the sector, with an estimated water footprint of 743 m^3 per kilogram of PGM produced (Haggard et al., 2015). Similarly, data from Palabora Mine reported average water use of 2.99 m^3/ton of copper ore between 1994 and 2012 (Mudd et al., 2017), while Black Mountain Mine recorded 0.76 m^3/ton of iron ore processed between 2012 and 2013 (Mudd et al., 2017). These variations reflect the influence of ore type, grade, processing complexity, and technology used.

It is also important to highlight that the reprocessing of gold tailings, a growing trend in mine waste valorization especially in South Africa, typically incurs even higher water consumption. This is largely due to sluicing operations and the pumping of tailings over long distances to centralized leaching plants, both of which demand significant volumes of water. These factors make efficient water management increasingly critical as the industry expands into lower-grade ores, tailings recovery, and more energy- and water-intensive technologies.

Table 1 Provides a comparative summary of water use across selected commodities in the South African mining and mineral processing industry.

Although mining and metal extraction operations typically account for a relatively small share of national water consumption, their local and regional impact can be significant, especially in water-scarce regions where these activities may compete directly with other critical water users (Rankin, 2011). This is particularly evident in arid areas, where mining operations often depend on groundwater sources of variable quality, placing stress on already limited water supplies. In such contexts, the intensive water demands of mining can reduce both the quantity and quality of water available for essential activities such as agriculture and domestic use. Furthermore, mines operating below the water table must be actively dewatered, a process that lowers the local water table and can adversely affect adjacent landscapes, stream flows, and groundwater-dependent ecosystems (Prosser et al., 2011). This hydrological disruption poses significant risks for nearby communities and the environment. While current practices at many decommissioned sites focus on treating and discharging mine water into river systems, more ambitious efforts are needed to treat mine-affected water to potable standards, enabling safe reuse and reducing pressure on freshwater sources. In addition, water pollution remains a critical concern. Effluents from mining and mineral processing often contain toxic metals, residual chemicals, and hydrocarbons, which can degrade surface and groundwater quality. This contamination undermines the availability of clean water for communities, ecosystems, and agricultural productivity.

Table 1
Water consumption for metal production.

Material Produced	Type of feed	Process flow	Water consumption (m^3) Per tonne metal	Per tonne ore
Steel	Oxide, 44wt % Fe	Mining-beneficiation-blastfurnace-basic oxygen furnace.	2.9	1.8
copper	Sulfide, 3wt % Cu	mining-comminution-flotation-smelting-converting-electrorefining.	25.9	0.7
Gold*	Gold ore; 3.6 g/t	Mining-comminution-flotation-cyanidation-electrowinning.	0.25×10^6–0.38×10^6	0.8
PGMs	PGM ore	Mining-comminution-flotation-leaching-refining.	0.67×10^6–1.8×10^6	0.5–2

* General consumption for high grade ore; tailings reprocessing will use more volumes

Combined with the limited capacity to develop new water infrastructure in many regions, these challenges heighten the potential for conflict between mining operations and local stakeholders who rely on shared water resources. Addressing these issues demands a proactive approach: mining companies, scientists, and researchers must collaborate to develop innovative water-saving technologies, enhance treatment processes, and optimize water use efficiency across the entire mineral value chain. Such interventions are essential to ensure the long-term sustainability of mining in water-stressed regions and to build trust with surrounding communities.

The urgency of such interventions is evident in South Africa, where recurring water shortages have had tangible economic consequences for the mining sector. For example, between 2014 and 2015, both Khumani Mine and Black Mountain Mine faced severe disruptions in water supply that led to reduced metal output and revenue losses (Mudd et al., 2017). To mitigate such risks, the industry is increasingly turning toward efficient water management strategies rooted in the reduce, reuse, and recycle framework. These approaches align with the principles of closed-loop water systems, which aim to minimize freshwater intake and wastewater discharge. Recognized for their superior efficiency compared to once-through systems, closed-loop systems hold immense promise for enhancing water security, reducing environmental impacts, and promoting sustainable mineral extraction, particularly in regions vulnerable to climate and infrastructure constraints. It is only when mines consciously decide to adopt a view of water stewardships that such strategies become central to the sustainability of the minerals extraction industry.

The adoption of recycling and wastewater management systems is a key strategy increasingly used by mining and mineral processing plants to reduce reliance on freshwater resources and move toward closing the water loop. Another emerging approach is the implementation of a water management hierarchy in conjunction with the reduce, reuse, and recycle principles. This approach acknowledges that different mining and metal extraction activities require varying levels of water quality. By reusing lower-quality water (e.g., for dust suppression or equipment cooling), companies can minimize the need to treat large volumes of wastewater, thereby conserving higher-quality treated water for processes that demand it.

This tiered use of water becomes especially critical in water-scarce regions, where access to freshwater is limited. In such contexts, the debate around whether water is treated as a right or a privilege becomes highly relevant. For instance, in Chile's copper mining sector, the increasing use of desalinated water has raised equity concerns (Delgado et al., 2021). Since desalination is often more costly and controlled by private operators, access to this water tends to favor industrial users over local communities, leading to tension around water justice and affordability (Pahl-Wostl, 2019). These dynamics underscore the need for policy frameworks that prioritize equitable access while promoting sustainable and efficient water use across mining operations.

South Africa and Chile have emerged as key testbeds for implementing water-saving strategies in mining, driven by acute water scarcity and increasing pressure to improve environmental stewardship. In South Africa, Anglo American, has advanced its "Water-Less Mine" vision under the broader FutureSmart Mining™ program (Anglo American Picture 2025). At the Mogalakwena platinum mine, the company has piloted technologies such as Coarse Particle Recovery (CPR) and non-aqueous separation, aimed at significantly reducing freshwater use in ore separation and transport. These innovations have the potential to reduce water consumption by 30–40 % per unit of mineral production. The urgency of this initiative became especially clear during prolonged droughts, when Mogalakwena's reliance on groundwater led to water shortages for local communities. In response, Anglo American invested over $250,000 to restore community water access, highlighting the link between water efficiency and social responsibility (Mudd et al., 2017). Similarly, in Chile's water-stressed copper sector, Anglo American has piloted hydraulic dewatered stacking (HDS) and dry processing at sites like the El Soldado mine (Newman et al., 2023).

An effective water management system can significantly improve mining sustainability, as demonstrated by several other South African mining companies. Gold Fields, for instance, has made strong commitments to water stewardship as part of its 2030 ESG goals, targeting 80 % water reuse and recycling, and a 45 % reduction in freshwater use. As of 2023, the company had already achieved close to 75 % recycled water use and a 39 % reduction in freshwater consumption (Gold Fields Water Stewardship 2025). Similarly, Sibanye-Stillwater's Marikana operation has implemented an integrated water management plan that includes alternative groundwater sourcing, upgrading pollution control dam linings, constructing new containment structures, deploying scavenger boreholes, and installing strategically placed water treatment plants to maximize reuse. One notable innovation is the use of aquifer storage and recovery, storing surface water underground to reduce evaporation losses, which can later be accessed for domestic, agricultural, or environmental use.

Khumani Mine also responded proactively to water shortages in 2015 by launching the Olifantshoek water project, installing on-site water storage facilities, and adopting paste technology, which enabled the recovery of up to 85 % of processed water, ensuring continuous operations and more efficient water use. Similarly, after a dispute over water disposal with its host community, Nkomati Nickel Mine converted one of its pits into a water storage facility. To ensure both safety and sustainability, the mine implemented dewatering technology to reclaim and recycle water from the pit (Mudd et al., 2017). Various dewatering technologies for mineral processing and metallurgical operations have been explored in the literature (Adewuyi et al., 2024), and while effective, these methods can alter water chemistry, potentially affecting metal recovery (Di Feo et al., 2021). Therefore, optimizing these systems requires detailed experimentation and simulation to mitigate any adverse effects of dissolved minerals in recycled water.

Beyond inland operations, the use of lower-quality and alternative water sources, such as seawater, offers another important strategy to reduce reliance on freshwater supplies (Gálvez and Cisternas, 2017). A leading example is Minera Esperanza's copper and gold mine in Chile, located in one of the driest regions on earth, approximately 180 km from Antofagasta. To meet its water needs, the mine was designed with a processing plant that uses seawater, marking a shift toward more resilient water sourcing models in arid mining regions. A supply pipe network was constructed to transport seawater 145 km from the Pacific coast to the mine site.

South Africa, with its 2800 km of coastline along both the Atlantic and Indian Oceans, has similar potential to leverage seawater or high-salinity groundwater as an alternative to freshwater. Doing so could significantly alleviate the pressure on limited freshwater reserves. However, integrating seawater into mineral processing systems presents technical challenges that must be carefully considered during plant design. These include potential chemical interactions between dissolved salts in seawater and the minerals being processed, as well as corrosion or scaling effects on plant equipment and materials. One way to mitigate these risks is to desalinate the seawater before use. However, desalination comes with its own trade-offs: energy consumption can account for up to 50 % of a desalination plant's operational costs (Elimelech and Phillip, 2011), making it a more expensive and energy-intensive solution. Therefore, decisions around seawater use, whether treated or untreated, must balance economic, technical, and environmental factors to ensure long-term feasibility and sustainability.

While the water management strategies and emerging technologies discussed above, such as dry processing and seawater desalination, hold significant promise for building a more sustainable mining industry, their widespread adoption is often constrained by high financial and energy costs. In particular, energy-intensive processes like desalination can pose a major economic barrier for mining companies. To address this challenge, it is essential to either develop more affordable technologies or pair existing ones with sustainable, low-cost energy sources to enhance their viability. One such opportunity lies in integrating renewable energy, especially solar power, into water treatment and supply systems. Given the high solar irradiance in many mining regions and particularly in Southern Africa, solar energy can substantially offset the operating costs of desalination plants and water recycling systems, making these solutions more financially sustainable over the long term.

In parallel, advances in smart mining technologies offer additional pathways for improving water efficiency. The use of Internet of Things (IoT) sensors and artificial intelligence (AI) enables real-time monitoring and process optimization, allowing for dynamic adjustments that reduce water consumption without compromising metal recovery. Technologies such as magnetic resonance analysis and advanced ore-sorting sensors can further support water conservation by distinguishing between high- and low-grade ore, thereby promoting selective processing and minimizing unnecessary water use.

5. Energy

According to a report by Deloitte, energy represents one of the largest operational costs in the mining sector, accounting for approximately 30 % of total cash operating expenses (Ivory et al., 2016). This proportion is expected to rise as mining operations become more mechanized, shift to deeper deposits, and increasingly process lower-grade and more complex ores, all of which require significantly more energy for extraction and beneficiation. Additionally, with energy supply becoming less reliable in many regions, costs are likely to escalate unless alternative and resilient energy strategies are implemented.

As shown in Table 2, the mining sector's energy consumption varies across mineral-rich countries, often constituting a substantial share of national electricity use. This variation is influenced by factors such as ore type and grade, geological complexity, mining and processing technologies employed, and the operational efficiency of facilities. Energy is consumed across the entire mining value chain. It is required for ore excavation, haulage, and hoisting, as well as for transporting materials to processing facilities and moving waste to disposal sites (Rankin, 2011). During beneficiation, significant energy is used for crushing, grinding (comminution), sorting, and concentration. In the final metal extraction stages, pyrometallurgical processes (e.g., roasting, smelting) and hydrometallurgical processes (e.g., slurry heating, electro-winning) are particularly energy-intensive. However, in pyrometallurgical processes, energy demands are more nuanced. For instance, during the roasting of sulfide ores, the oxidation of sulfur is an exothermic reaction, meaning it generates heat. Depending on the sulfur content, this self-sustaining reaction can significantly reduce the external energy input required, thereby lowering overall energy costs. Nevertheless, this benefit must be balanced with the environmental impacts of sulfur dioxide emissions, which require additional treatment or gas capture systems to meet regulatory standards.

Given this broad dependency, energy is not just a cost factor, it is a strategic enabler of productivity, profitability, and sustainability in the mining sector. For policymakers, this underscores the importance of encouraging investment in energy-efficient technologies, diversifying energy sources, including renewables, and incentivizing innovations that lower energy intensity per unit of metal produced. Aligning energy strategies with both economic and environmental policy objectives will be essential for ensuring the resilience and long-term viability of mining operations in an increasingly resource-constrained world.

According to the Minerals Council South Africa, the country's mining industry accounts for as much as 30 % of Eskom's annual electricity supply (Business Tech South Africa Mining Industries 2025). In recent years, South Africa has faced a persistent energy crisis marked by frequent and prolonged power outages, making energy supply increasingly unreliable. This instability poses a serious risk to the mining sector, threatening the sustainability and profitability of operations. While some energy-intensive facilities, such as smelters, are essential for maintaining grid stability, there is a growing argument that reducing the mining and metal extraction sector's dependence on grid electricity could alleviate pressure on the national power system. Doing so would not only improve the mining industry's resilience but could also help make more energy available for other critical sectors and communities across the country.

Coal remains a vital component of South Africa's energy mix, particularly as a low-cost and accessible energy source for supporting industrial growth and economic development. For developing countries, coal has historically underpinned national energy security, and in South Africa, it continues to provide the majority of electricity supply. However, coal's dominance comes with significant environmental costs. The combustion of coal releases large volumes of greenhouse gases, such as carbon dioxide (CO_2) and nitrous oxide (N_2O), contributing to climate

Table 2
Electrical energy demand by the mining industry in mining-intensive countries.

Country	Electrical energy (% of national electricity)	Reference
South Africa	30	(Business Tech South Africa Mining Industries 2025)
Australia	15	(Australia DCCEEW 2025)
Canada	44 – 56 (provincial)	(BMU 2022)
USA	12	(EIA 2023)
Chile	30	(BMU 2022)
Peru	56	(Pérez Ortega, 2025)

change and ecological degradation. As a result, South Africa ranks 13th globally in CO_2 emissions, with per capita emissions exceeding both the global average and those of most other developing nations (Mirzania et al., 2023).

Given South Africa's ratification of the Paris Climate Agreement and its commitment to reducing national emissions, there is an urgent need for a managed transition toward more sustainable energy sources. While coal will remain part of the country's energy mix in the near term, policy must prioritize diversifying energy supply and reducing emissions from high-energy sectors such as mining and metal extraction. This transition presents an opportunity. In this context, the mining and metals industry must not only strive to improve energy efficiency and reduce overall consumption through integrated energy management strategies but also actively explore alternative, cleaner energy sources. Incorporating renewable energy into operations can lower long-term costs, enhance energy reliability, and support environmental goals, positioning the sector for resilience and competitiveness in a carbon-constrained future.

5.1. Renewable energy systems

A global shift is underway as countries transition from fossil fuel-based energy systems to renewable energy sources. These sources, such as solar, wind, hydroelectric, biomass, and geothermal, are increasingly being adopted to replace traditional carbon-intensive fuels. The growth in renewable energy's share of global primary energy consumption is gaining steady momentum each year, driven by the urgent need to enhance energy security and reduce greenhouse gas emissions to mitigate climate change.

Despite this global trend, South Africa's progress remains modest. According to the Council for Scientific and Industrial Research (CSIR), renewable energy accounted for just 11.9 % of the country's total energy mix in 2021 (Pierce and Ferreira, 2022). This lags significantly behind international benchmarks. For instance, Switzerland boasts one of the cleanest electricity profiles in Europe, with 60 % of its power derived from renewables. Germany currently generates approximately 40 % of its electricity from renewable sources and aims to reach 65 % by 2030 (Thimet and Mavromatidis, 2022). Meanwhile, Costa Rica has emerged as a global leader, producing 98 % of its electricity from renewable sources as early as 2018 (ITA Costa Rica's Renewable Energy 2025).

This lag in progress is due to a combination of structural and systemic challenges. South Africa remains heavily reliant on coal, with deeply entrenched infrastructure that makes shifting to cleaner energy technically and economically difficult. Regulatory delays, policy uncertainty, and limited investor confidence have slowed renewable energy deployment. Financial constraints and insufficient grid capacity further hinder integration of variable energy sources like solar and wind. Additionally, concerns over job losses in coal-reliant regions and limited public awareness create social and political resistance to change.

Despite these hurdles, efforts within the mining sector show encouraging signs of a gradual shift. In 2020, non-renewable sources still accounted for approximately 94 % of South Africa's overall energy use, including in mining, with renewables contributing just 6 %. However, several leading mining companies, such as Sibanye-Stillwater, Anglo American Platinum, Goldfields, Harmony Gold, Impala Platinum, and Pan African Resources, have committed to change, initiating solar photovoltaic (PV) projects totaling nearly 600 MW in capacity. For the mining sector to remain competitive and aligned with global sustainability targets, it must continue to expand its use of renewable energy to ensure long-term operational resilience and reduced environmental impact.

While large-scale hydroelectric power may be less feasible in South Africa due to its drought-prone climate, the country is exceptionally well-positioned to capitalize on solar and wind energy. South Africa enjoys significantly higher solar radiation than many northern hemisphere countries (Fig. 4), averaging between 4.5 and 6.5 $kWh/m^2/day$ compared to just 3.6 in parts of the U.S. and 2.5 in Europe and the U.K

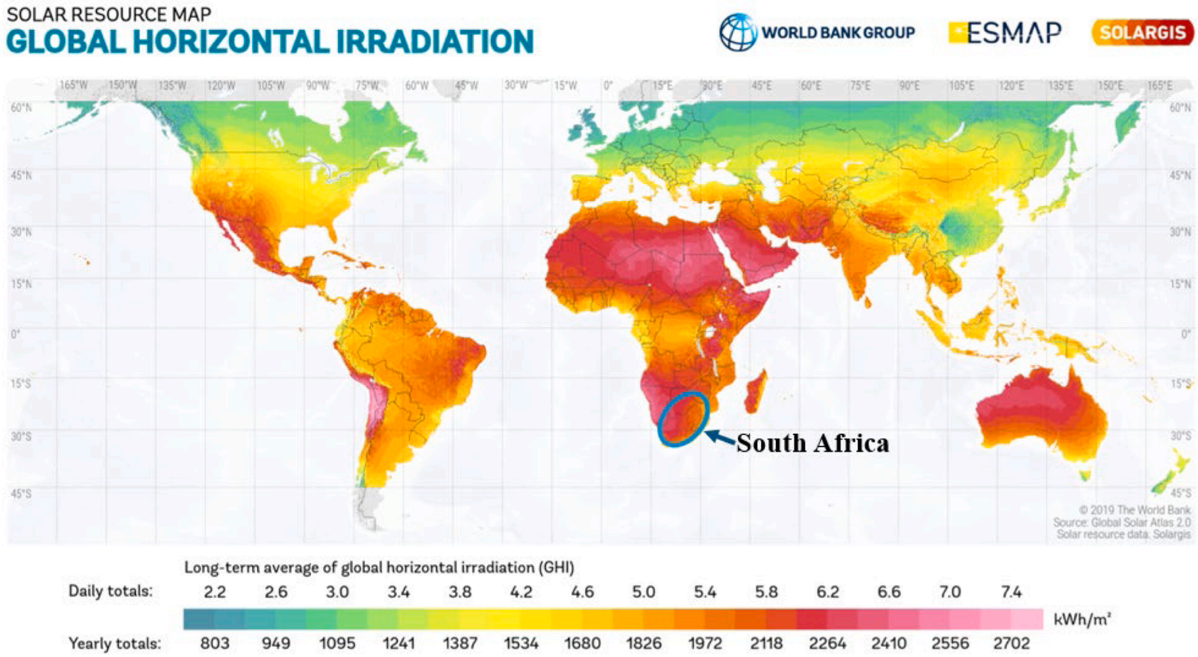

Fig. 4. Global horizontal Irradiation (after World Bank, source: https://globalsolaratlas.info/map?c=-25.168637,-22.71094,2&r=ZAF).

(WWF Renewable Energy 2025). According to the CSIR, the theoretical potential for wind energy in the country is vast, large enough to meet global electricity demand if fully exploited outside of protected and populated areas. This abundance of renewable energy resources presents a clear opportunity for South Africa's mining sector to reduce dependence on fossil fuels and embrace a more sustainable, resilient energy future.

While the shift toward renewable energy in South Africa's mining sector is promising, it also brings a new set of challenges that must be addressed to ensure reliability and long-term success. Although renewable sources like solar and wind offer clear benefits, including low operating costs and minimal carbon emissions, they are inherently intermittent and weather-dependent. The wind and sun are unpredictable by nature; the sun does not always shine and the wind does not always blow. Solar power generation peaks during midday and drops off at night, while wind turbines can only operate when wind conditions are favorable. Thus, on calm days, wind turbines sit still. This mismatch between energy supply and actual demand can lead to significant gaps, particularly during peak usage hours or periods of unfavorable weather. In countries with resilient energy infrastructure, these fluctuations are often balanced by feeding renewables into the national grid. However, South Africa's strained and unreliable grid makes it difficult to depend on this strategy. To effectively increase the share of renewables in the energy mix, particularly for energy-intensive sectors like mining, robust energy storage solutions are essential to ensure stability and supply continuity.

Energy storage systems play a critical role in balancing supply and demand by storing excess energy generated during peak production periods and releasing it when production drops or demand rises. Although promising advances are being made in technologies such as flow batteries and hydrogen storage, lithium-ion batteries remain the most widely used form of energy storage today. However, lithium-ion batteries rely on metals like lithium and cobalt, which are non-renewable and must be mined, often at significant environmental cost and with additional demands on water and energy. While efforts to recycle these metals from end-of-life batteries are increasing and vital for sustainability, there is also a need to match renewable energy generation with equally sustainable storage solutions.

One such alternative gaining traction is pumped storage (PS) hydropower, a renewable method of storing energy (Van Dongen and Bekker, 2020). This system works by pumping water from a lower reservoir to a higher elevation during times of excess energy production. When electricity is needed, the stored water is released downhill through turbines, generating power as it flows back to the lower reservoir. Pairing solar or wind energy with pumped storage systems can provide a highly effective and longer-term energy storage solution compared to lithium-ion batteries. On sunny or windy days, the surplus energy can be used to pump water uphill, which can then be released during periods of low generation or high demand, ensuring efficient and continuous energy supply. Recent studies show that, in response to the growing share of renewables, the number of pumped storage projects is rising globally, particularly in Europe and Asia, due to their flexibility and ability to reduce curtailment of wind and solar power (Van Dongen and Bekker, 2020).

While the availability of surface reservoir space and fresh water may limit the feasibility of conventional pumped storage hydropower in drought-prone countries like South Africa, abandoned or closed mine sites offer a promising and underutilized alternative. These sites, particularly deep underground mines, present significant opportunities for constructing underground pumped storage systems. A recent initiative in Sweden exemplifies this potential, where a consortium is developing an underground hydropower system using mine shafts, requiring only two water storage points with at least a 50-meter elevation difference (WWF Renewable Energy 2022). According to the report, the deeper and wider the mineshaft, the more power can be extracted from the plant, and the larger the mine, the higher its storage capacity. Given that South Africa hosts six of the ten deepest mines in the world, including Mponeng mine at 3.9 km deep, the country is uniquely positioned to leverage this approach for large-scale, long-duration energy storage. In regions where freshwater is scarce, researchers have proposed using mine water instead. During mining operations, dewatering systems are installed to manage groundwater inflows. After mine closure, water levels must still be managed to maintain safety and ecological balance. These artificially maintained reservoirs can be repurposed for industrial or potable water supply, ecological flow support, or energy generation through geothermal and hydropower applications (Álvarez et al., 2021). Successful examples of mine water reuse in Europe underscore both technical feasibility and environmental safety, provided that proper containment and monitoring systems are in place to mitigate contamination risks.

In parallel, disused tailings ponds can be repurposed as solar ponds capturing thermal energy from the sun. Although this technology has not yet been widely adopted, a study in Chile estimated that such systems could generate up to 626 GWh annually, demonstrating potential for supplementary power generation in mining regions (Garrido et al., 2012).

For South Africa, where over 6000 abandoned mines exist, the potential to convert these sites into renewable energy hubs is significant. However, realising this vision requires thorough evaluation of site-specific environmental risks such as water contamination or structural collapse, economic cost-benefit analyses, and a supportive regulatory framework that enables land access, investment, and long-term operational oversight. If effectively implemented, such initiatives could not only enhance national energy resilience but also catalyse socio-economic revitalization in former mining communities, creating jobs and transforming post-mining landscapes into drivers of sustainable development.

Innovative energy storage technologies that move beyond traditional hydropower are also emerging, such as Underground Gravity Energy Storage (UGES) systems (Hunt et al., 2023). This approach generates electricity by lowering sand into abandoned underground mines, harnessing its potential energy through regenerative braking. When electricity prices are low, the sand is lifted back to the surface, storing energy for later use, functioning similarly to a gravity battery based on the principle that "what goes up must come down" by converting the potential energy of a heavy weight object into electricity. In the context of South Africa, gravity batteries hold strong potential when integrated with solar or wind power systems, reducing reliance on the national grid and the country’s embattled power utility, Eskom. Notably, if sand can be used in these systems, then the vast quantities of solid waste generated by the mining industry could also serve as an energy storage medium. This represents a transformative opportunity to advance a low-carbon energy transition while simultaneously addressing the pressing challenges of mining waste management and land rehabilitation. From a policy standpoint, repurposing existing mining infrastructure for UGES offers a dual benefit: enhancing national energy security and enabling productive post-mining land use. Moreover, exploring the substitution of sand with mining solid waste in these systems could significantly improve their sustainability by tackling both energy storage and waste management concerns in tandem. To enable broader adoption of such innovations, however, comprehensive feasibility assessments are essential, examining site-specific geological conditions, potential environmental impacts from large-scale material handling, and the regulatory landscape governing mine closure and land reuse. With appropriate support, UGES could emerge as a compelling model for integrated energy and mining policy, promoting both the energy transition and circular economy objectives.

Globally, solar and wind have emerged as the most widely adopted renewable energy sources in the mining sector, with solar accounting for approximately 86 % of renewable energy systems implemented, particularly in regions like Australia and Chile (Limpitlaw, 2021). However, many mining companies are increasingly turning to hybrid renewable energy systems, combining sources to enhance energy reliability and support both economic and environmental sustainability (Igogo et al., 2020). Despite the promising geothermal potential in parts of Africa (e.g. East Africa Rift Valley), there has been no documented use of this energy source within the continent’s mining sector. The slow uptake can be attributed to the high upfront capital costs, lengthy project development timelines, and technical challenges related to drilling and resource management, which make geothermal less attractive compared to faster-to-deploy solar and wind options. Additionally, limited infrastructure and financing mechanisms hinder the commercial scale deployment of geothermal in mining. Similarly, biomass technology remains largely unexplored for energy generation in African mining. This is partly due to limited access to sustainable biomass feedstocks near mining sites, concerns over supply chain logistics, and the lack of targeted policies or incentives to integrate biomass into mining energy portfolios. Overall, the untapped potential of geothermal and biomass in Africa suggests opportunities for diversification. Overcoming financial, technical, and policy barriers will be critical to expanding the renewable energy mix in the continent’s mining sector.

5.2. *Other energy-saving strategies*

As presented in Fig. 3, the closed-loop metal resource management is a pathway for a circular economy as well as an energy-saving strategy in the metal industry. Recovery of metals from waste material is a crucial way to reduce energy demand in the mining industry, as energy is used only for metal recovery, unlike in primary ore, where energy is needed from mining up to the metallurgical process. Research showed that the energy required for zinc and iron recovery from steel scrap is one-third of that required to recover the same tons from primary minerals, using a hydrometallurgical approach. Also, findings suggest that “alternative anode reaction technology (AART)” can reduce the hydrometallurgical energy of copper recovery operation by up to a quarter of the conventional method from primary ores (Alam, 2023). Furthermore, deployment of electrification and automation has, in recent years, shown high potential to improve mining efficiency and reduce energy consumption in the mining industry. This approach has been widely adopted by Canadian mining companies to enhance off-grid energy capacity and promote long-term energy sustainability (Issa et al., 2023). Due to the increasing energy requirement of the Australian mining sector, which increased by 5.8 % in 10 years and accounts for 15 % of electricity generation in Australia (as at 2023), the mining sector continues to increase investment in electric trucks and other off-grid electrification projects, to reduce reliance on the national grid supply (Australia DCCEEW 2025). The South African mining industry should adopt these strategies to curb intermittent energy supply shedding that usually affects the smooth running of mining, beneficiation and metallurgical operations.

6. Concluding remarks

Technological advancements and the drive towards meeting green energy transition targets for global economies suggest that the demand for metals will continue to increase significantly in the future. This suggests that mining companies will need to increase production levels of critical metals needed through either an increased production from primary sources or /and further exploring alternative secondary sources. Such an increase in production level will however, have to be coupled with an associated increase in the critical inputs needed in the production value chain. It is important to note that the high demand for metals is also accompanied by calls for more accountable and responsible mining from both investors and the communities in which the mines operate. While the value of metals in the society is clearly phenomenal, their extraction should be done in a sustainable manner that does not compromise the living conditions of the current and future generation.

Water and energy are two of the major inputs that play a significant role in the transformation of host ores to metallic components. However, the challenges associated with the supply of these two inputs in the South African mining industry suggest a need for companies to reevaluate their approach to the metal extraction value chain in order to minimise negative societal impacts and maximise social sustainability. The discussion presented in the paper suggests that while leveraging the water-energy nexus in the mining sector is very important, it requires an approach that involves strategic innovations in water and energy management through a closed-loop approach. The incorporation of sustainability principles in the initial process design, considering lower impact options investing in renewable energy supplies, capturing and reusing waste energy, employing technologies and strategies that reduce water usage, are some of the approaches that have to be considered. Furthermore, the adoption of agendas such the African Agenda 2063, the UNSDGs and the ESGs can go a long way in ensuring that mining companies play a role in not only decoupling economic activity from the consumption of finite resources but also in moving the world towards carbon neutrality.

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