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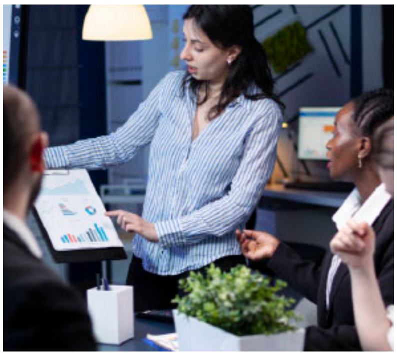

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FOREWORD

It is my pleasure to welcome you to this inaugural Southern African Institute of Mining and Metallurgy conference 'ESG in the Minerals Industry – Challenges and Opportunities' and the hospitality of the Glenburn Lodge & Spa, situated within the Cradle of Humankind – a World Heritage Site.

Traumatic global military conflicts, the ever-increasing impact of climate change, surging nationalistic sentiment, politics and depressed global economics have made addressing environmental, social and governance (ESG) matters in business increasingly challenging. Under these trying circumstances it can be difficult to focus on the long game and prioritise long-term sustainability as "time is short, survival takes precedence, and every other issue seems more urgent". Sadly, this short-term sentiment has led to social backlash and deep scepticism that ESG has become superficial 'greenwashing' rather than genuine efforts towards long term sustainability. Within this context ESG-Sustainability in mining faces many challenges, economic pressures, regulatory complexity and uncertainty, data and reporting integrity, capital allocation, technological integration, supply chain management, community and stakeholder expectations, and environmental impact locally, regionally and potentially globally, now and decades into the future. However, despite these challenges the industry is making progress, driven by the need for sustainable practices to deliver the minerals and metals that underpin the technology- driven world that we now take for granted.

Responsible mineral industry organisations are focussing on energy efficiency, water conservation and biodiversity preservation with sustained effort to positively impact the lives of employees and mining communities as South Africa cycles through a difficult period of low economic growth, heightened unemployment and political realignment. Concurrently there is growing understanding that true sustainability comes, not from regulatory compliance alone, but through building social capital and strengthening stakeholder relationships that lead to an enduring social licence to operate.

I trust that the proceedings of this conference will allow you to build the additional perspective that enables you to rise to the challenge of embedding ESG in your professional lives and businesses. I encourage you to participate in the proceedings, debate the issues and enjoy networking with solution-oriented people on this journey to enable environmental and social sustainability in the minerals Industry.

Finally, a heartfelt thank you to the Organising Committee, the SAIMM conferencing team and our willing and generous sponsors, without whom this conference would not have been possible.

Take care and please stay safe.

Gordon Smith
Chairperson of the Organising Committee

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NAIDU CONSULTING

A framework for applying LCA and industrial ecology philosophy to support local renewable energy value chains to drive the just transition

D. Viljoen, J.M. Kruger, M. Solomon, J. Browne, and P. Mtemeli

Carbon Neutral Energy Systems, South Africa

The mining industry is increasingly recognised as a key player in driving global efforts towards carbon neutrality, with many companies setting ambitious targets and developing comprehensive roadmaps to reduce their carbon footprint. Beyond the environmental agenda, the mining sector also faces the challenge of ensuring sustainable post-mine economies for host and affected communities. This paper explores how complementary methodologies - life cycle assessment, social life cycle assessment and industrial ecology - can be applied to connect the inventory of resources within the mine, its surrounding communities, and renewable energy interventions. By linking these inventories, synergistic opportunities for economic diversification and post-mine closure planning are identified. This approach seeks to leverage carbon neutrality efforts not only to mitigate climate impact but also to drive sustainable development, creating new economic opportunities that support resilient communities long after mining activities have ceased.

INTRODUCTION

The call for low-carbon and renewable energy systems has long been sounded, with their necessity underscored by intensifying climatic abnormalities (NCEI, 2024) (Betts, 2024). The urgent need to address climate change has prompted a global movement towards carbon neutrality. Achieving this goal necessitates a holistic approach that considers environmental, social, and economic factors. Carbon neutrality interventions include replacing fossil fuels with wind, solar, hydropower, and biobased energy, purchasing and/or retiring carbon credits, and improving energy productivity through technological and operational advancements.

Mining companies have been leading the charge in developing carbon neutrality roadmaps. The South African mining sector already has over 100 renewable energy projects with a potential generation of 10.4 GW of electricity (Stoddard, 2024). The impetus is due to the pressure of the international community, tax tariffs such as carbon tax as well the new carbon border adjustment mechanism (CBAM) (which assigns a tax to any product entering the European Union based on its carbon footprint). Additionally, changes in leadership and paradigm shifts are driving a move away from fossil fuels. Regardless of whether this change is due to goodwill or financial incentives, the move from fossil fuel-based energy to renewable energy, especially by the energy intensive mining sector, is of global benefit.

Likewise, mining companies are becoming increasingly proactive in ensuring that the benefit accrued from mineral extraction is shared by all. This is evident in companies' corporate social responsibility plans, social and labour plans, and regional economic development projects as well as resources put into providing skills development, training and scholarships to mine-affected stakeholders. A crucial factor in ensuring meaningful and inclusive benefits is the consideration of life post-mine closure and the impact closure has on local and regional economies, as well as the economies of labour sending areas.

Concurrent Economic Diversification and Post Mine Succession Planning (Solomon, 2019), is an essential intervention to ensure that mine-affected communities are not at risk of socio-economic collapse post mine-closure.

Combining the issue of fossil fuel-based energy and its lead role in climate change with the inclusive and sustainable benefit to be accrued from mineral extraction, we position this as part of the Just Transition, in which the decarbonising of the mining industry's activities can drive inclusive benefits of its affected communities.

Methodologies whose philosophies can guide this Just Transition are life cycle assessment (LCA), social life cycle assessment (S-LCA) and industrial ecology (IE). An LCA is a systematic method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle. This includes the extraction of raw materials, manufacturing, distribution, use, and disposal. While a LCA measures environmental impacts, an S-LCA evaluates the social and socio-economic impacts of products or activities throughout the mining life cycle, from extraction to disposal. IE is an interdisciplinary field that aims to optimise material and energy flows in industrial systems to mimic natural ecosystems. The objective is to reduce waste, resource consumption and process costs, while ensuring economic and social benefits for all stakeholders in this industrial ecosystem.

This paper explores how aspects of LCA and IE can be applied in a framework to support the Just Transition of the mining industry: providing carbon neutral energy while ensuring equitable and sustainable outcomes for stakeholders in the mining value chain.

OBJECTIVES

The overarching objective of this proposed framework aligns with the broader goal of linking environmental sustainability with socio-economic development, ensuring that the mining industry's transition to carbon neutrality also contributes to a fair and just future for all stakeholders, especially mining-affected communities.

The first specific objective is to demonstrate how LCA and S-LCA can be applied to mining operations and renewable energy interventions to develop inventories which can be used to identify economic opportunities.

The second specific objective is to apply industrial ecology to identify synergistic opportunities between the inventories of mining activities and renewable energy projects.

BACKGROUND

Mining Life Cycle and Value Chain

The mining life cycle refers to the series of stages that a mining project undergoes from initial exploration to the final closure and rehabilitation of the site when mineral resources have been depleted or when mining the orebody becomes economically unviable. The typical stages of the mining life cycle include:

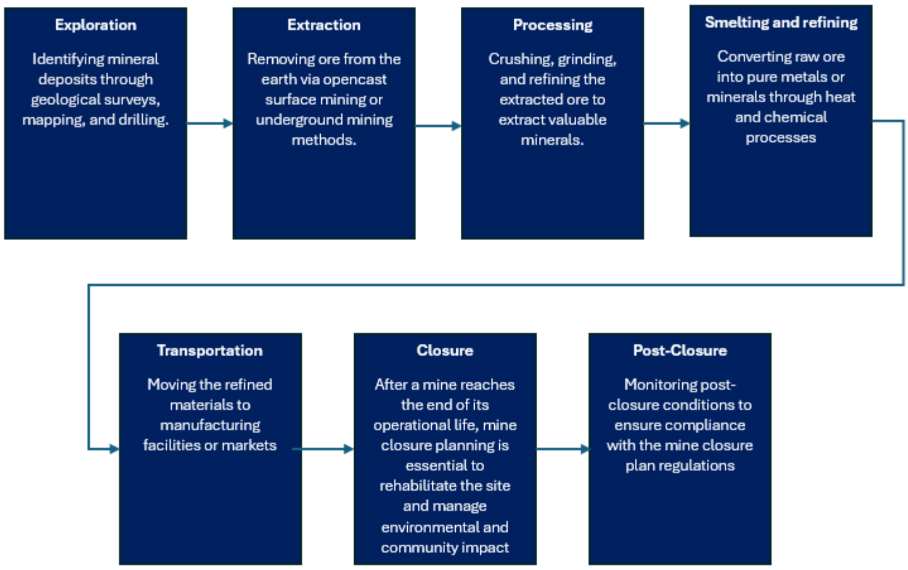

Figure 1. The mining life cycle (Durucan, et al.*, 2006).*

Within the mining life cycle sits the value chain of the mine, which is defined as the processes which creates direct value for the mining operation. In contrast to the mining life cycle, the mining value chain therefore encompasses all activities involved in transforming raw materials from extraction to market delivery (Voster, 2001). The current mining value chain follows a linear flow of material where products produced from the metals or minerals extracted during mining ends up as waste, either on dump sites or as pollution in cities or natural environments.

The mining industry therefore faces several significant challenges that impact both the environment and society. Resource depletion is a critical concern, as many essential minerals, such as rare earth elements, lithium, and copper, are finite and concentrated in specific geographic regions, rendering supply chains vulnerable to geopolitical risks and resource scarcity. Additionally, mining operations often lead to environmental degradation, resulting in extensive habitat destruction, soil erosion, water contamination – such as acid mine drainage – and loss of biodiversity. The sector is also characterised by high energy consumption, predominantly relying on fossil fuels, which contributes to greenhouse gas emissions. Furthermore, the extraction and processing of minerals generate substantial waste, including toxic tailings and slag, which can harm the environment if not managed effectively. The prevailing linear model of extract-use-dispose in mining emphasises insufficient material recovery, reuse, and recycling. Lastly, the social impact of mining can be profound, often leading to community displacement, labour exploitation, and conflicts over land and resources.

Life Cycle Assessment

One of the defining features of an LCA is the detailed breakdown of a product or service into its constituent parts, thus allowing for each step's environmental impacts to be accounted for holistically (Yao, *et al.*, 2021). Additionally, an LCA can assist in identifying economic opportunities in the value chain where raw materials can be sourced by identifying the waste resources from other industries. (Durucan, *et al.*, 2006).

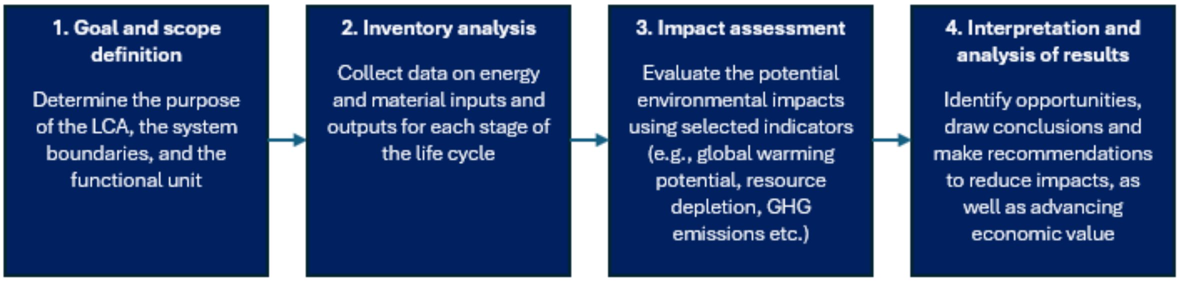

Figure 2. Key stages of an LCA 1(Tyagi, 2024).

A comprehensive and holistic impact analysis provides an understanding of the environmental impacts associated with different stages of the mining life cycle, allowing for targeted interventions. By identifying environmental hotspots within a product's life cycle and addressing these hotspots, mines can significantly reduce their overall environmental impact, including greenhouse gas emissions, energy consumption, and waste generation. Through the assessment of resource use at each stage of a product's life cycle, opportunities for more efficient resource utilisation can be identified, such as how the value chains from other industries can integrate by turning wastes into resources. This can lead to the adoption of alternative materials or processes that are more sustainable, ultimately preserving valuable resources. These opportunities assist in making informed decisions on how to implement more effective and sustainable carbon neutrality strategies (Golsteijn, 2024).

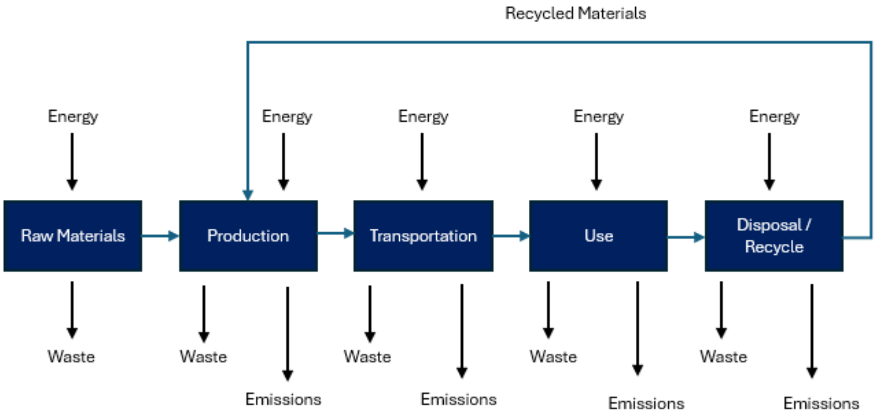

Figure 3. Example of elements considered in the life cycle assessment of a product (Mirjana, 2023).

Social Life Cycle Assessment

S-LCA is a tool for understanding and addressing the social impacts of mining on affected communities. Mining projects can lead to many disruptions to the livelihoods of local and host communities. Examples include dust and noise pollution; the displacement of local communities resulting in loss of homes, land, and livelihoods; introduction of social dynamics such as prostitution and increased alcohol and drug use in local communities; and the destruction of eco-system services on which communities rely. S-LCA evaluates the extent of displacement, compensation processes, and the respect of land rights, particularly for indigenous groups. By evaluating factors like labour conditions, community health, land rights, and economic benefits, S-LCA can help ensure that mining is conducted in a way that respects human rights and promotes social well-being. It is a tool which can support the broader goal of sustainable development by ensuring that the mining sector contributes positively to local communities while minimising harmful social impacts (Springer, *et al.*, 2020).

In the context of mining, S-LCA focuses on the effects of mining activities on the well-being of affected communities, workers, and other stakeholders, and therefore addresses the social dimensions, emphasising human rights, land ownership, labour conditions, health, safety, and community development (Bouillass, *et al.*, 2021).

Industrial Ecology

IE promotes sustainable development through the optimisation of material and energy flows, the closing of resource loops, and the creation of symbiotic relationships between industries. A defining feature of IE is the development of a circular economy where the waste from one process or industry is a valuable resource for another process or industry, which entails the identification of the inputs and outputs of various industrial processes and linking them in an appropriate manner. Systems thinking is applied to view industrial processes as part of a larger system that includes ecological and social dimensions, therefore promoting resilience and adaptability of the mining industry, making them better suited to respond to environmental and economic changes. Waste is minimised while maximising resource efficiency by mimicking natural processes to ensure material and energy flow optimisation. Cooperation between different industries to utilise each other's by-products and waste materials are therefore facilitated (LI, 2018).

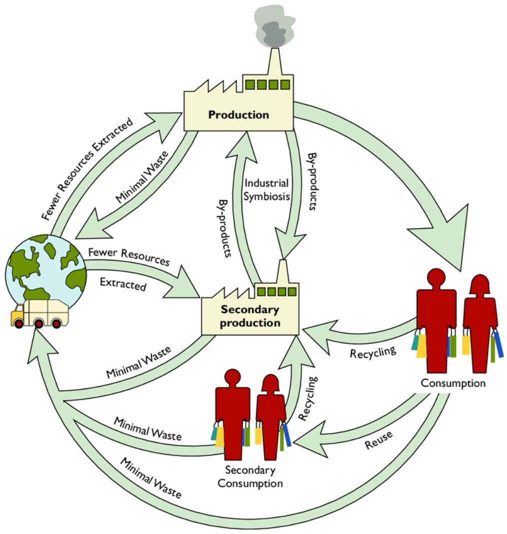

Figure 4. Closed loops and circular economies in an industrial ecology (Wu, et al.*, 2013).*

Carbon Neutrality Interventions

Carbon neutrality interventions encompass a range of strategies aimed at achieving a balance between emissions produced and those removed from the atmosphere. These interventions are essential for mitigating climate change and are increasingly recognised as vital components for sustainable development in the mining industry (Chen, *et al.*, 2022). Interventions include renewable energy technologies implemented to reduce impact from energy generation and consumption, and includes technologies such as solar and wind, as well as renewable fuels like biogas. The urgency of addressing climate change has prompted industries to shift from fossil fuel dependence towards cleaner energy sources, aiming for net-zero carbon emissions. Solar and wind energy are increasingly recognised for their potential to provide abundant, low-cost electricity while significantly reducing greenhouse gas emissions (GHG). Biogas, derived from organic waste or purposely grown feedstocks, not only contributes to energy generation but also aids in waste management. These renewable technologies are therefore environmentally friendly but also economically viable, fostering job creation and energy security. As industries implement initiatives to implement these technologies, they contribute to a more resilient and sustainable energy infrastructure, ultimately supporting the global goal of carbon neutrality (Dong, *et al.*, 2021).

The Just Transition

The Just Transition framework is a critical approach aimed at ensuring that the shift towards a low-carbon economy is fair, equitable and inclusive, particularly for vulnerable communities and workers affected by industries that are heavily reliant on fossil fuels, such as mining. The concept framework emphasises the need for social dialogue among workers, unions, employers, and governments to secure decent jobs and livelihoods during this transition. In the mining sector, where jobs are often tied to coal and other carbon-intensive resources, the Just Transition seeks to mitigate the adverse impacts of decarbonisation by providing retraining opportunities, social protection, and new employment avenues in sustainable industries. This approach not only addresses economic displacement but also aligns with broader climate goals by fostering a transition that uplifts affected communities while combating climate change. As countries commit to reducing their carbon footprints, integrating Just Transition principles into mining policies becomes essential for achieving both environmental sustainability and social equity (UNDP, 2022).

South Africa especially aims to promote a Just Transition that addresses the specific needs of developing nations, particularly those across the African continent. In a statement made by President Ramaphosa at the UN Secretary-General's Climate Action Summit in September 2019, he emphasised the necessity of implementing measures that focus on workforce re-skilling, job creation, social protection, and the development of new green sectors. This includes diversifying economies that are heavily reliant on coal and formulating labour and social strategies as ageing coal-fired power plants are phased out. The overarching goal is to build a climate-resilient society that guarantees decent work for all, fosters social inclusion, and eradicates poverty. Special attention must be given to protecting vulnerable groups affected by climate change, including women, children, individuals with disabilities, the economically disadvantaged, and the unemployed, while also safeguarding workers' jobs and livelihoods (Novotny, 2021).

Scope of Work

This paper borrows concepts from LCA, S-LCA and IE to link renewable energy projects for economic opportunities to support a sustainable post-mine economy. This paper does not provide a definitive solution but rather proposes a framework and perspective for exploring potential opportunities in linking carbon neutrality and renewable energy interventions to the sustainability of post-mine economies and livelihoods.

Additionally, this paper does not:

- Consider all possible carbon neutrality and renewable energy interventions.
- Conduct an LCA.
- Define or rely on a functional unit.
- Quantify environmental impacts.
- Account for all flows (energy, materials, and social flows) in the inventory. In practice, many additional energy, material, and social flows exist but are not addressed here.
- Perform comprehensive IE linkages but rather illustrates the concept.

Methods

To demonstrate the potential that LCA, S-LCA and IE philosophies can have when applied to carbon neutrality and renewable energy interventions and their role in achieving the Just Transition, it is necessary to first understand the mining and the renewable energy value chain. This lays the foundation for applying LCA, S-LCA and IE principles. Next, the mining and renewable energy value chains are broken into composite parts, forming inventories. Finally, the synergies between the inventories that are deemed to have social and economic benefits for the mining affected communities are identified and discussed.

FUNDAMENTAL VALUE CHAINS

Mining Process

The initial system of interest is the mining process which, amongst other requirements, requires energy throughout the process. Taking a generic view of a mining process, we arrive at the following diagram.

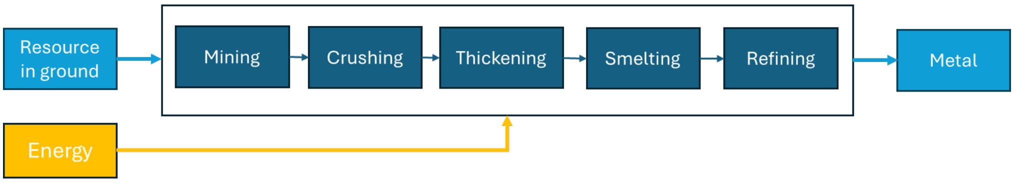

Figure 5. Mining process flow diagram.

Renewable Energy Interventions

The mining industry and thus mining processes exist in an environment with several sustainability imperatives and pressures. Factors relevant to decarbonisation of energy sources include but are not limited to the following: economic, social and governance investing: GHG emissions, climate change; Just Transition; carbon tax; and CBAM. Considering these factors, the aggregated energy source in Figure 1, 'energy', can be supplied by renewable sources. Thus, Figure 2 is updated to include a range of renewable energy sources, including but not limited to: solar PV, wind, biogas, hydrogen, and biomass.

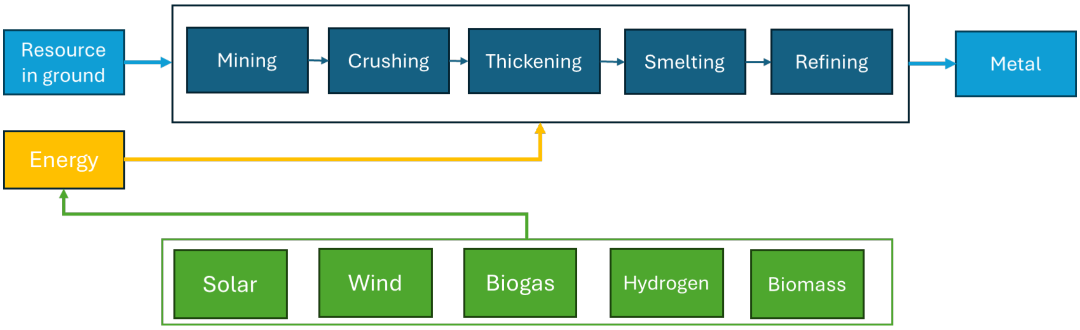

Figure 6. Mining process flow diagram + renewable energy options.

Inventories

Having established the mining and renewable energy systems, the next step is to apply an LCA approach to these two parallel components: define the relevant inventories. In this paper, the inventories are categorised as follows.

INPUTS	OUTPUTS
From Environment	Product and By-product
From Technosphere	To Environment (air)
From Society	To Environment (water)
	To Environment (other)

The approach taken in this step deviates from traditional LCA in the following ways:

- It does not include all the material and energy flows associated with the process.

- It includes social components (e.g., education and unemployment.)

Mining Value Chain Inventory
First, one considers only the mining process and creates an inventory of the flows in and out of the mining value chain that are relevant to the Just Transition.

This inventory is shown below:

INPUTS	OUTPUTS

From Environment
• Resource in ground
• Ground and surface water
From Technosphere
• Explosives
• Chemicals
• Energy
  o Electricity
  o Coal
  o Natural gas
• Mining and processing equipment
• Spares
From Society
• Skilled and unskilled labour
	Product and By-product
	• Ore, concentrate, un-refined mineral or refined metal
	• Waste rock and tailings
	• Tyres
	To Environment (air)
	• Greenhouse gases (GHGs) from manufacturing processes and fossil fuels (e.g., CO2, NOx, SOx)
	• Dust and noise
	To Environment (water)
	• Water returned to water bodies
	To Environment (other)
	• Land damage
	To Society
	• Skills
	• Unemployment (retrenchment or end life of mine)
	• Mining communities

The diagram of the mining value chain is updated to include the LCA and S-LCA inventory.

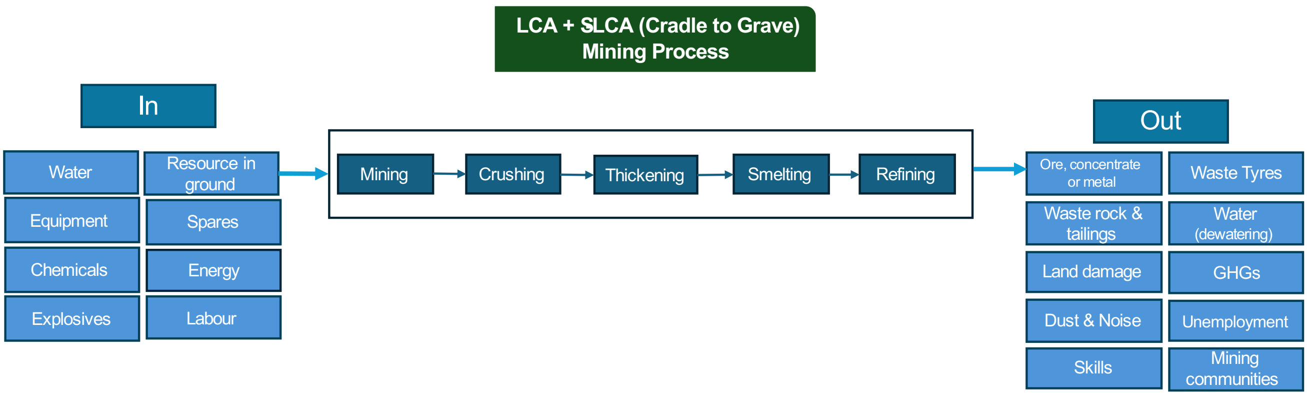

Figure 7. LCA and S-LCA Inventory applied to the mining value chain.

Renewable Energy Value Chain Inventory
Following from the mining value chain, the same process is followed for the renewable energy value chain. This paper will use solar PV, wind and biomass fuel/biogas as examples.

Solar PV

INPUTS	OUTPUTS
From Environment • n/a **From Technosphere** • Electricity (for manufacturing processes, primarily derived from fossil fuels in many regions) • Silicon (for photovoltaic cells) • Glass (for panels) • Metals (aluminium for frames, silver for conductive layers, and copper for wiring) • Plastics (for encapsulants and backing sheets) • Water (for cooling and cleaning during manufacturing) **From Society** • Skilled and unskilled labour for mining, manufacturing, installation, and maintenance	**Product and By-product** • Clean, renewable electricity generated by solar panels • Manufacturing waste (scrap materials, chemicals) • End-of-life waste (recycling or disposal of panels after their lifespan) **To Environment (air)** • GHGs from manufacturing processes (e.g., CO2, NOx, SOx) • Potential toxic emissions from the production of silicon and other chemicals **To Environment (water)** • n/a **To Environment (other)** • n/a **To Society** • n/a

Wind Turbines

INPUTS	OUTPUTS
From Environment • n/a **From Technosphere** • Metals (steel for towers, copper for electrical components, rare earth elements for magnets in turbines) • Fibreglass and carbon fibre (for turbine blades) • Concrete (for foundations) • Electricity (for manufacturing components, primarily derived from fossil fuels) • Oil and lubricants (for maintenance of moving parts) **From Society** • Skilled and unskilled labour for mining, manufacturing, installation, and maintenance	**Product and By-product** • Clean, renewable electricity generated by wind turbines • Manufacturing waste (scrap materials, chemicals) • End-of-life waste (recycling or disposal of turbine components, particularly blades) **To Environment (air)** • GHGs from manufacturing processes (e.g., CO2, NOx, SOx) • Minimal emissions during operation **To Environment (water)** • n/a **To Environment (other)** • n/a **To Society** • n/a

Biogas

INPUTS	OUTPUTS
From Environment • n/a **From Technosphere** • Electricity and heat (to assist the anaerobic digestion process) • Chemicals (potentially for soil pH adjustment and nutrient fertiliser addition) • Water (for slurry preparation) • Biomass feedstock (if purposely grown) • Organic waste (animal manure, food waste, agricultural residues) **From Society** • Skilled and unskilled labour for collection, processing, and maintenance	**Product and By-product** • A mixture of methane (CH4) and carbon dioxide (CO2), used for electricity, heat, or as a vehicle fuel • A nutrient-rich by-product that can be used as a fertiliser • Minimal solid waste, primarily managed as digestate **To Environment (air)** • Leakage: A mixture of methane (CH4) and carbon dioxide (CO2) • GHGs from the combustion of biogas (CO2, CH4 if not fully combusted) • Odours and potential ammonia emissions from digestate handling **To Environment (water)** • n/a **To Environment (other)** • n/a **To Society** • n/a

The diagram of the renewable energy value chain is updated to include the LCA and S-LCA inventory.

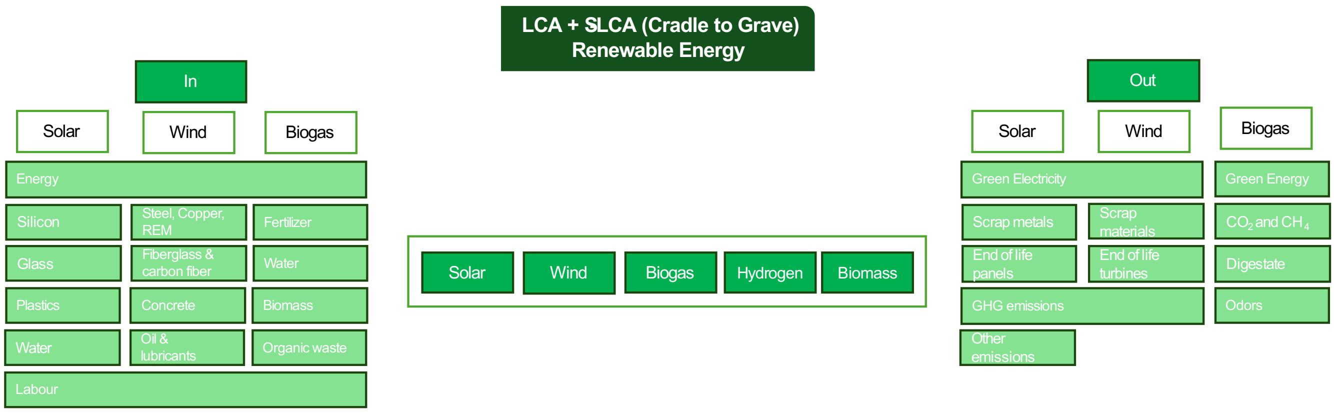

Figure 8. LCA and S-LCA inventory applied to the renewable energy value chain.

Industrial Ecology

With the inventories defined, the principles of IE can be applied. The first step is to combine all the inventories, as shown in the following diagram:

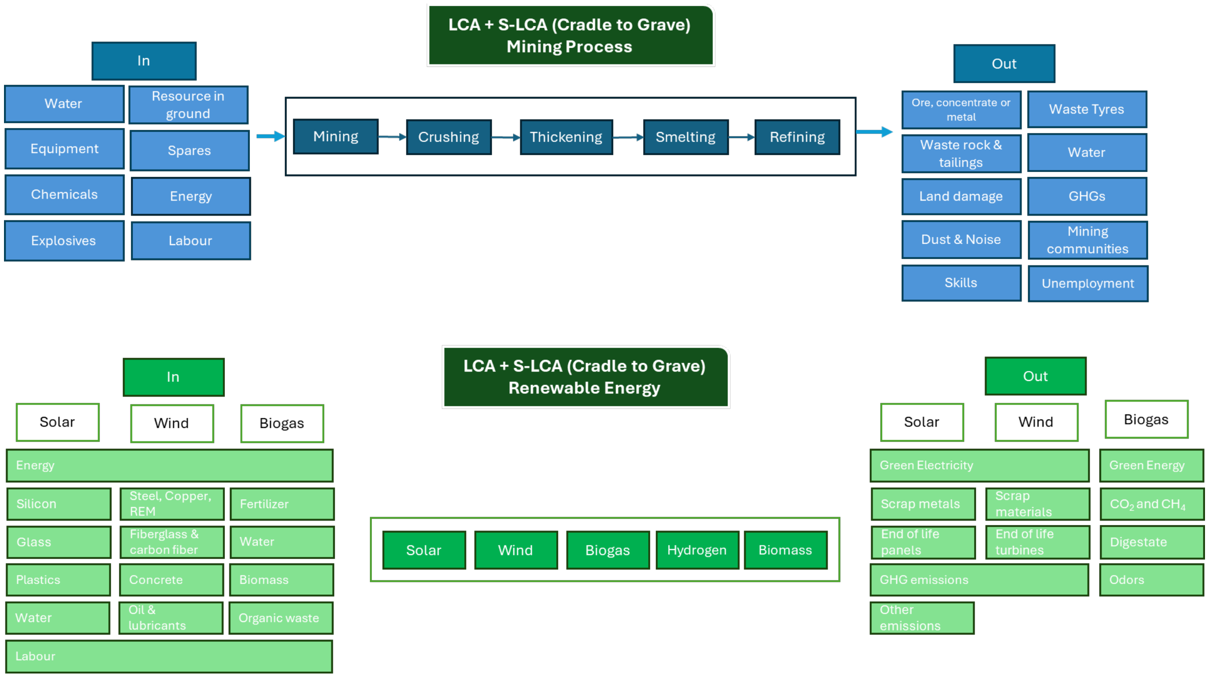

Figure 9. Combined value chains and inventories.

The next step is to conceptualise the linkages that exist between the inventories. Table provides examples of linkages and explains their significance.

Table 1. Example of inventory linkages.

1. Water from the mining value chain → Water from the biogas value chain
The dewatering of mines may result in available water for alternative economic opportunities. Water is pre-requisite for almost all human and economic development. In this example, the water can be used for biomass production which will be turned into biogas, a carbon neutral energy source.

2. Unemployment from mining value chain → Labour from the renewable energy value chain
Point 2 and 3 have similarities but speak to different factors. When the mines slow down production towards end of life, retrenchment is inevitable. With this, there will be unemployed men and women. If there is a local renewable energy value chain, these people can find direct employment, and the local sector would provide indirect employment.

3. Mining communities from mining value chain → Labour from renewable energy value chain
When a mining operation begins, it attracts people who wouldn't have ordinarily settled in that location. Therefore, being cognisant of the mining communities that were formed because of the mine is the responsible thing to do. Therefore, the mining communities will have people who are looking for employment, and once again, the local renewable energy value chain can provide direct and indirect employment.

4. Skills from mining value chain → Labour from renewable energy value chain
The labour that leaves the mines will be skilled, semi-skilled and un-skilled. A local renewable energy value chain will have the need for all types of labour.

5. Biomass from biogas value chain → Land damage from mining value chain
Biogas can be produced through anaerobic digestion of biomass. Likewise, biomass fuel pellets can be made from compressed biomass. Both are renewable and low carbon fuels. Biomass can be grown on mine damaged land. This provides both economic activities, as well as remediating damaged land.

6. Green electricity/energy from renewable energy value chain → energy from renewable energy value chain
The green electricity or energy that is produced via the solar, wind or biogas technology can be used in a local renewable energy value chain. If there is local manufacturing of renewable energy technology or equipment, these processes could use the renewable energy produced. If a mine has a renewable energy installation, this energy can be used for the local renewable energy value chain post-mine closure.

7. Green electricity/energy from renewable energy value chain → energy from mining value chain
The use of green electricity/energy in the mining value chain. This is already commonplace.

8. Green electricity/energy from renewable energy value chain → explosives from renewable energy value chain
The mining industry uses explosives that require ammonia in their production. There is an opportunity to use renewable energy to produce the ammonia, and thus create local production of green explosives and/or fertilizer.

9. Digestate from the biogas value chain → Land damage from the mining value chain
The production of biogas in an anaerobic digester creates a valuable by-product: digestate. This is a nutrient rich liquid stream which can be used for the remediation of mine affected/damaged land. The ideal would be to use this on the biomass feedstock, which is grown on mine damaged land, as this is a recycling loop, ensuring minimal loss of both nutrients and water.

The connections are illustrated in Figure 10.

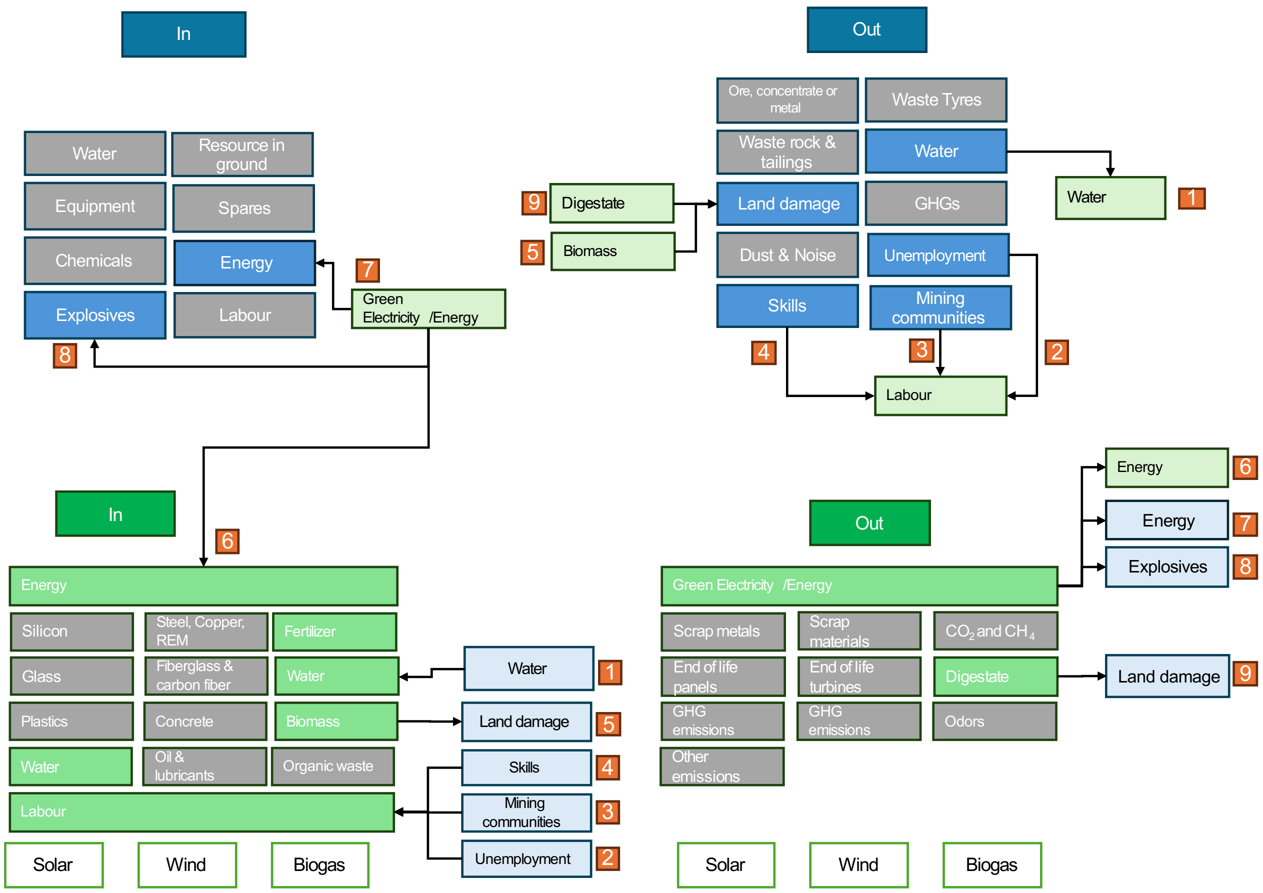

Figure 10. Inventories with industrial ecology linkages.

FINDINGS

When analysed through the lens of LCA, S-LCA and IE, mining and renewable energy technology value chains reveal interconnections throughout their life cycles. By analysing the full spectrum of inputs and outputs across the entire life cycle of carbon neutral energy systems and mining operations, we can better identify areas of opportunity.

It was found that inventories can be made which include both conventional LCA inputs and outputs, such as materials, emissions and energy, as well as social factors such as unemployment and skills.

Additionally, it was found that consolidating all the inventories provides a good platform for identifying linkages which support the ideation of local renewable energy value chains. As more linkages are identified, there are more potentials to realise these local value chains while ensuring that mine communities have a sustainable post-mine economy.

The nine connections that were made are by no means exhaustive or perhaps even realistic, but they illustrate how these synergies should be viewed and plotted.

CONCLUSIONS

To achieve carbon neutrality and a Just Transition, it has been proposed in this paper to integrate the methodologies of an LCA and S-LCA together with the philosophy of IE. The framework set out in this paper provides a high-level concept for assessing and mitigating the environmental and social impacts of mining operations through well planned renewable energy projects. The development of new sustainable industries and the optimisation of existing ones can create jobs and economic opportunities, particularly in regions dependent on traditional industries.

By employing LCA and S-LCA, we created an inventory of the mining and renewable energy value chains, which identifies hotspots across the life cycle of products and processes. These hotspots become focal points for applying IE principles to facilitate alternative economic opportunities. Simultaneously, the principles of IE enable us to design systems that mimic natural ecosystems, where waste from one process becomes the input for another, promoting circularity and resource efficiency.

Incorporating S-LCA into this framework ensures that the social impacts of carbon neutrality interventions are equally prioritised. S-LCA assesses how interventions affect stakeholders, including mine workers, their families and local communities. This approach highlights issues such as labour rights, community health, land use, equity in resource distribution, and the well-being of mining-affected communities involved in the extraction of key minerals for renewable energy technologies. By addressing these social dimensions, S-LCA ensures that the benefits of the low-carbon transition are equitably shared and that vulnerable groups are not disproportionately impacted, fostering a truly Just Transition.

In conclusion, a framework that incorporates LCA, S-LCA, and IE into the mining value chain and its renewable energy interventions is useful for guiding the industry, its governance and legal frameworks, as well as internal and external stakeholders toward truly sustainable and equitable pathways in the fight against climate change and ensuring a Just Transition for all stakeholders involved.

REFERENCES

Betts, A., 2024. *Monday was hottest recorded day on Earth: 'Uncharted territory'*. [Online] Available at: https://www.theguardian.com/environment/article/2024/jul/24/record-hottest-day-earth-temperature-july

Bouillass, G., Blanc, I. & Perez-Lopez, P., 2021. Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *Int J Life Cycle Assess 26,* p. 2408–2435.

Chen, L., Msigwa, G. & Yang, M., 2022. Strategies to achieve a carbon neutral society: a review. *Environ Chem Lett,* Volume 20, p. 2277–2310 .

Dong, F., Qin, C., Zhang, X., Zhao, X., Pan, Y., Gao, Y., Zhu, J. & Li, Y., 2021. Towards Carbon Neutrality: The Impact of Renewable Energy Development on Carbon Emission Efficiency. *Int J Environ Res Public Health,* 18(24).

Durucan, S., Korre, A. & Munoz-Melendez, G., 2006. Mining life cycle modelling: a cradle-to-gate approach to environmental management in the minerals industry. *Journal of Cleaner Production,* 14(12-13), pp. 1057-1070.

Golsteijn, L., 2024. *Pre-sustainability.* [Online] Available at: https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/ [Accessed 18 09 2024].

LI, X., 2018. *Industrial ecology and industry symbiosis for environmental sustainability - Definitions, Frameworks and Applications.* s.l.:Sheffield Hallam University.

Mirjana, R., 2023. Chapter 3 - Strategies for sustainable energy management. In: *Sustainable Energy Management (Second Edition).* s.l.:Academic Press, pp. 35-94.

NCEI, N., 2024. *U.S. Billion-Dollar Weather and Climate Disasters (2024).* [Online] Available at: https://www.ncei.noaa.gov/access/billions/

Novotny, P.-A., 2021. *Webber Wentzel.* [Online] Available at: https://www.webberwentzel.com/News/Pages/what-does-the-just-transition-look-like-in-south-africa.aspx [Accessed 26 09 2024].

Review, M., 2023. *Mining Review.* [Online] Available at: https://www.miningreview.com/industry-insight/conscious-circularity-the-role-of-mining-in-a-circular-economy/ [Accessed 18 09 2024].

Rossi, F., Zuffi, C., Parisi, M.L., Fiaschi, D. & Manfrida, G.,, 2023. Comparative scenario-based LCA of renewable energy technologies focused on the end-of-life evaluation. *Journal of Cleaner Production,* Volume 405.

Solomon, P. M., 2019. *Economic Succession Planning, economy beyond mining.* s.l., SAIMM.

Springer, S., Peregovich, B. & Schmidt, M., 2020. Capability of social life cycle assessment for analyzing the artisanal small-scale gold mining sector—case study in the Amazonian rainforest in Brazil. *Int J Life Cycle Assess,* Volume 25, p. 2274–2289.

Stoddard, E., 2024. *SA mining sector leads renewable drive, headwinds include skills shortage and mineral rights opacity.* [Online] Available at: https://www.dailymaverick.co.za/article/2024-02-07-sa-mining-sector-leads-renewable-drive-headwinds-include-skills-shortage-and-mineral-rights-opacity/

Tyagi, S., 2024. *Life Cycle Assessment: Understanding the Five Stages of LCA.* [Online] Available at: https://askelsustainabilitysolutions.com/life-cycle-assessment-understanding-the-five-stages-of-lca/
[Accessed 18 09 2024].

UNDP, 2022. *United Nations Development Programme.* [Online] Available at: https://climatepromise.undp.org/news-and-stories/what-just-transition-and-why-it-important
[Accessed 26 09 2024].

Upham, D. P., Sovacool, P. B. & Ghosh, D. B., 2022. Just transitions for industrial decarbonisation: A framework for innovation, participation, and justice,. *Renewable and Sustainable Energy Reviews,* Volume 167.

Voster, A., 2001. Planning for value in the mining value chain. *The Journal of The South African Institute of Mining and Metallurgy.*

Wu, Z., Edgeman, R. & Laasch, O., 2013. Principles of Responsible Management: Sustainability, Responsibility, Ethics. In: *United Nations Principles for Responsible Management Education (PRME) textbook.* s.l.:s.n.

Yao, K.A.F., Koffi, Y.B., Belcourt, O., Salze, D., Théophile, L., Lopez-Ferber, M., Junqua, G., 2021. Mining impacts assessment using the LCA methodology: case study of Afema gold mine in Ivory Coast. *Integrated Environmental Assessment and Management,* 17(2), pp. 465-479.

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David is a chemical engineer with a specialisation in sustainable mineral development. He is dedicated to ensuring that all stakeholders in the mining industry, including the environment and mining communities, receive inclusive benefits. As a co-founder and director of C-NES and a director at Minecare Evolution, David has worked extensively as a sustainability engineer. His expertise spans bio-based carbon neutrality, energy management, economic diversification, waste-to-energy solutions, post-mine succession planning, and environmental stewardship.

David's notable projects include designing economic diversification strategies and creating an energy and GHG emissions management guideline for a major platinum mine, implementing a clean cook stove program in West Africa, and assisting in the development of the National Mine Closure Strategy.

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Sustainability Engineer
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Jean-Marc is an industrial engineer who started his career as a business improvement consultant in the mining industry, with a focus on applying systems thinking, lean principles, operation modelling and project management tools in various improvement projects. Since moving into the sustainability field, Jean-Marc has had the opportunity to develop and implement carbon reduction and renewable energy projects for various mining companies. His aim is to contribute to a sustainable future for the mining industry, its surrounding communities and environment, through the advancement and integration of Carbon Neutral and Circular Economy systems. Jean-Marc submitted and presented a paper titled '*PGM mining and processing in the circular economy: a framework towards circularity*' at the SAIMM 8th International PGM conference held in Sun City.

Back to the Future: Reverse engineering TSFs for the end land use

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The closure of tailings storage facilities (TSFs) is one of the most challenging aspects in the mining sector due to the intricate environmental, social, and economic risks they present. Addressing these risks sustainably requires not merely adhering to regulatory norms but envisioning a future where these landscapes can regenerate and rejuvenate local ecosystems and communities. This paper explores an innovative approach to reverse engineering TSFs to meet sustainable closure objectives and proposes integrating closure planning into the TSF lifecycle as early as possible. The critical question examined is whether we can design a TSF that not only minimises its environmental footprint but also regenerates. The framework for successful TSF closure is multifaceted, involving different stakeholders: tailings engineers focus on physical stability, owners aim for visually integrated and rehabilitated facilities, regulators prioritise liability management and risk assessment, and local communities seek benefits to the environment. Advanced tools such as dam breach assessments, rain-on-grid modelling, landform evolution modelling, rendered images are utilised to bridge the gap between technical complexities and stakeholder understanding. These tools validate design assumptions, predict long-term performance, and visually communicate outcomes to non-technical audiences. Emphasising ecological and sociocultural integration, the paper aligns TSF closure practices with broader environmental, social, governance, and sustainability goals, ensuring the revitalisation of the environment and tangible benefits for local communities.

INTRODUCTION

Background on the closure of tailings storage facilities

Effective management of tailings, both during and after mining, is the long-term responsibility of mining companies and is subject to varying regulatory regimes throughout the life of an operation, from initial feasibility through to closure and post-closure (ICMM, 2021). The closure of tailings storage facilities (TSFs) is widely recognised as one of the most challenging aspects in the mining sector due to the intricate environmental, social, governance, and economic risks they present. These facilities must be managed and monitored long after the cessation of mining activities to prevent potential environmental contamination and to ensure public safety and community well-being (ICMM, 2021). Effective closure strategies require comprehensive planning and long-term financial commitments to stabilise the tailings and rehabilitate the surrounding environment (EPA, 1994). Additionally, mining companies must engage with local communities to address social concerns and ensure that post-closure activities promote sustainable development (Franks *et al*., 2011).

Importance of sustainable closure

Addressing the risks associated with TSFs in a sustainable manner necessitates more than mere adherence to regulatory norms; it requires a visionary approach where these landscapes are transformed to regenerate and rejuvenate local ecosystems and communities.

Sustainable closure practices go beyond achieving compliance; they incorporate ecological restoration and socio-economic revitalisation into the design and management of TSFs. This holistic approach fosters biodiversity, enhances ecosystem services, and provides socio-economic benefits to local communities (Environmental Agency, 2004). For example, integrating ecological and social considerations early in the TSF lifecycle can lead to innovative reclamation strategies that create habitats for native species and provide recreational or agricultural opportunities for local populations (Murphy & Cooney, 2014). By promoting the regeneration of affected areas, the long-term environmental footprint of mining activities can be minimised, contributing to the overall sustainability goals of the sector. This forward-thinking strategy aligns with the principles of sustainable development, where environmental, social, and economic dimensions are harmoniously balanced (Brundtland Commission, 1987).

Objectives of the paper

This paper delves into the innovative approach of reverse engineering TSFs to ensure they meet sustainable closure objectives. Rather than treating closure planning as the final step after cessation of mining activities, it is proposed to integrate such planning into the TSF lifecycle from the earliest stages. This proactive approach aims to address the long-term environmental, social, governance (ESG) and economic risks associated with TSF management by embedding sustainability into the design, operation, and closure of these facilities. The critical question that this paper seeks to explore is: can we design a TSF that not only minimises its environmental footprint but also contributes to ecological regeneration and socio-economic benefits? By addressing this question, we aim to demonstrate that sustainable closure is achievable through innovative engineering practices, comprehensive stakeholder engagement, and the application of advanced modelling and monitoring tools. The ultimate objective is to provide a framework that supports the mining industry's broader ESG and sustainability (S) goals, promoting a transformative shift towards more resilient and sustainable post-mining landscapes.

CHALLENGES IN TSF CLOSURE

The closure of tailings storage facilities presents a myriad challenges that are both multifaceted and complex. These challenges can be broadly categorised into ESG, economic and integrated risks, each constituting a significant aspect of the sustainable closure paradigm.

While most civil engineering projects are designed to last for several decades, the lifespan of TSFs extends well beyond these typical timelines. This concept is illustrated in Figure 1, where the final segment of the timeline features a break (not to scale) to represent the uncertain duration beyond the closure of the TSF.

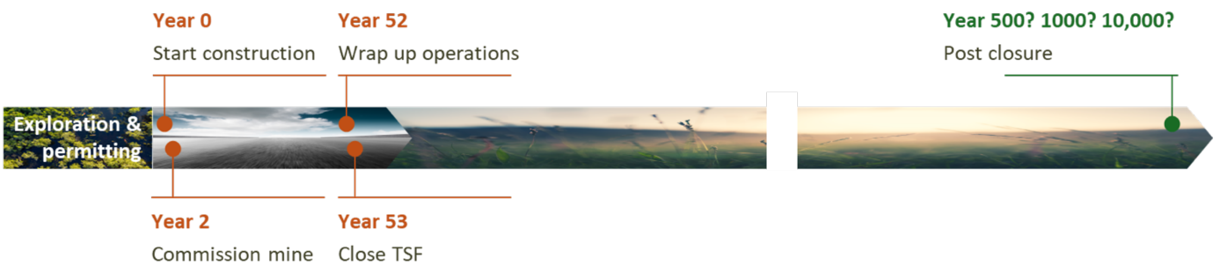

Figure 1. Lifecycle of a typical TSF.

Environmental Risks

Environmental risks associated with TSF closure are primarily concerned with preventing contamination and ensuring the long-term stability of the facility. Tailings materials often contain hazardous substances that, if not managed correctly, can migrate into surface and subsurface environments, posing serious environmental threats (Lottermoser, 2011). Additionally, the physical stability of TSFs must be maintained to prevent failures that could result in catastrophic releases of tailings material (Evans *et al*., 2015). Erosion, hydrological changes, and vegetation growth further complicate the environmental management of closed TSFs, necessitating continuous monitoring and adaptive management practices (Hancock *et al*., 2008).

Social Risks

The social implications of TSF closure are equally significant. Local communities that live near mining operations often face prolonged exposure to environmental risks, which can impact their health, safety, and livelihoods (Owen and Kemp, 2013). Effective closure strategies must therefore include robust community engagement efforts to address these concerns and ensure that the post-closure land use aligns with community needs and aspirations (Franks *et al*., 2011). This could involve transforming TSFs into areas for recreation, agriculture, or wildlife conservation, thereby creating socio-economic opportunities for the affected communities (Murphy & Cooney, 2014).

Governance Risks

Governance risks in TSF closure encompass regulatory compliance, corporate governance, financial assurance, stakeholder engagement, institutional capacity, and ESG alignment. Ensuring strict adherence to regulations avoids legal penalties and reputational damage (Morrison-Saunders *et al*., 2008; EPA, 1994). Effective governance guarantees accountability and transparency, mitigating planning and financial risks (ICMM, 2021). Adequate financial resources secured through bonds or trust funds are crucial, as mismanagement can lead to incomplete closure (Paterson and Dormuth, 2011). Robust stakeholder engagement ensures transparent communication, preventing mistrust and conflicts (Franks *et al*., 2011). Adequate institutional capacity with skilled personnel and resources is essential for effective closure (Mackenzie, 2011). Aligning closure practices with ESG criteria preserves commitments to sustainability and social responsibility, safeguarding the company's social licence to operate (Brundtland Commission, 1987).

Economic Risks

The economic aspect of TSF closure revolve around the substantial financial commitments required for comprehensive closure planning and implementation. While TSFs are typically designed to adhere to all operational requirements—such as maintaining adequate capacity at an acceptable factor of safety at the lowest possible cost—the post-closure life of a mine far outweighs the operational portion (ICMM, 2021). The economic burden of closure includes not only the costs of stabilisation and rehabilitation but also the long-term expenses associated with ongoing monitoring, maintenance, and potential remediation efforts (McCullough and Lund, 2006). Ensuring that these financial commitments are met requires strategic planning and often the establishment of financial assurance mechanisms to cover the full costs of closure and post-closure activities (Paterson and Dormuth, 2011). Standardised, but simpler, methods of determining financial provisions are commonly used by regulators. However, the financial quantum should ideally be supported by appropriate closure plans and designs.

Integrated Challenges

In addition to these individual challenges, TSF closure is further complicated by the need for integration across ESGS and economic dimensions. A holistic approach to closure recognises that these elements are interdependent and must be addressed collectively to achieve sustainable outcomes (Morris and Binns, 2011). This necessitates innovative engineering practices, comprehensive stakeholder engagement, and the application of advanced modelling and monitoring tools to ensure that TSFs can transition from operational facilities to rehabilitated landscapes that provide environmental, social, governance, and economic benefits.

STAKEHOLDER PERSPECTIVES

The importance of stakeholder engagement in TSF management is emphasised by the Global Industry Standard on Tailings Management (GISTM) developed by the International Council on Mining and Metals (ICMM), which underscores the need for continuous, transparent dialogue with all stakeholders to ensure safety and mitigate risks throughout the TSF lifecycle (ICMM, 2020). A number of role players are involved with mines and their TSFs. Depending on the stakeholder, the view may be short-, medium-, or long-term and could be in- or outwardly facing. Each stakeholder has the potential to contribute constructive inputs into the overall picture if appropriately engaged, with Figure 2 illustrating such an engagement session.

Figure 2. Community engagement session (image generated using Microsoft Designer.)

Tailings engineers
Tailings engineers, as the Designer(s) of Record and/or the Engineer(s) of Record, are primarily concerned with the physical stability of TSFs. Their focus is on designing and maintaining facilities that can safely contain tailings material while minimising the risk of failure. This involves detailed engineering analysis and the application of advanced modelling techniques to predict and mitigate risks associated with tailings storage (Blight, 2010). Beyond the primary focus of ensuring stability, cognisance is taken of possible environmental pollution.

Owners
The owners' perspective is often driven by the imperative to demonstrate that their TSFs have been rehabilitated effectively and no longer pose any latent liabilities. This requires comprehensive closure planning and execution to ensure that the facility integrates visually and functionally with the surrounding environment, thereby passing stringent regulatory and community scrutiny (Mackenzie, 2011).

Regulators
Regulators play a critical role in overseeing the closure process to ensure compliance with environmental standards and public safety. Their primary focus is on liability management and risk assessment, requiring mining companies to provide detailed closure plans, financial assurances, and continuous monitoring to mitigate any long-term risks associated with TSFs (ICMM, 2021).

Local communities
For local communities, the closure of TSFs represents an opportunity to transform these facilities into assets that can benefit the community. This can include converting lands into recreational spaces, agricultural areas, or wildlife reserves, thus enhancing local quality of life and contributing to sustainable development (Owen and Kemp, 2013). Effective stakeholder engagement is crucial to align post-closure land use with community needs and interests (Franks *et al.*, 2011).

Receiving environment
The receiving environment, which includes the local ecosystems and biodiversity, is an implicit stakeholder in the TSF closure process. The focus here is on fostering biodiversity and regeneration, ensuring that rehabilitated TSF areas support the growth of native species and contribute to ecological balance. Sustainable closure practices must prioritise ecological restoration to mitigate the long-term environmental impacts of mining activities (Murphy & Cooney, 2014).

INNOVATIVE APPROACH: REVERSE ENGINEERING TSFS

Concept of reverse engineering in TSF closure

Reverse engineering in the context of TSF closure involves proactively incorporating closure and post-closure considerations into the upfront design and operational phases of a TSF. Unlike the traditional approach, which typically only considered closure designs after mining activities cease, reverse engineering integrates closure objectives from the outset. By embedding closure needs into the TSF lifecycle, facilities become easier, more cost-effective, and environmentally robust to close and rehabilitate. The approach emphasises sustainability, stakeholder engagement, and the use of advanced monitoring and modelling tools to ensure a smooth transition from operation to closure.

Integration of closure planning into the TSF lifecycle

Integrating closure planning into the TSF lifecycle is fundamental to the reverse engineering approach. This means considering closure requirements during the design phase and establishing adaptive management practices throughout the facility's operation. Early closure planning involves:

- Developing detailed closure plans alongside TSF design to anticipate potential ESGS and economic challenges. This could include modifying the outer slope geometry, concurrent placement of cover materials, inclusion of an operational spillway, etc.
- Implementing continuous monitoring and predictive modelling to assess the TSF's performance and inform adaptive management strategies. This allows the proposed closure designs to be assessed, and modified if necessary, during the operational phase of the TSF.
- Engaging stakeholders, including local communities, regulators, and environmental organisations, from the project's inception to ensure transparency and address concerns early. Early and ongoing involvement allows for adaption of the closure plan and proactive adjustments.

By incorporating these elements, mining companies can create TSFs that align with long-term sustainability goals and regulatory requirements.

Designing TSFs for minimal environmental footprint and regeneration

Designing TSFs for a minimal environmental footprint and regeneration is a core goal of the reverse engineering approach. This involves:

- Choosing materials and construction methods that enhance the TSF's stability and environmental protection.
- Implementing design features that facilitate land reclamation and ecological restoration, such as creating conditions that support native vegetation growth and wildlife habitats.
- Utilising advanced technologies and sustainable practices, such as rain-on-grid (RoG) modelling and landform evolution modelling (LEM), to predict and minimise long-term environmental impacts.
- Planning for the post-closure use of TSF land in ways that benefit local communities, such as converting it into recreational areas or agricultural lands.

By integrating these principles, TSFs can transition from operational facilities to rehabilitated, or even regenerated, landscapes that support biodiversity, ecological balance, and socio-economic development.

ADVANCED TOOLS AND TECHNIQUES

The sustainable closure of TSFs requires the application of advanced tools and techniques that can anticipate and manage various environmental and socio-economic challenges. These tools enhance our ability to model, visualise, and predict the outcomes of different closure strategies, thereby fostering a more integrated and effective approach to TSF management. By leveraging innovative technologies such as dam breach assessments (DBAs), RoG and LEM modelling, and rendered images and videos—alongside insights derived from natural systems—engineers can develop robust closure plans that align with ESGS goals, facilitating more effective communication with diverse audiences.

Dam breach assessments
DBAs are critical for predicting the consequences of potential failures of TSFs. These assessments model the dynamics of a dam breach scenario, estimating the flow paths, velocities, and inundation extents of released tailings material (Evans *et al*., 2015). DBAs enable engineers to understand the risks posed to downstream communities and ecosystems, ensuring that appropriate mitigation measures are incorporated into closure plans. By identifying vulnerable areas and evaluating the potential impact, DBAs contribute to the development of safer and more resilient TSFs (Paterson and Dormuth, 2011), improve emergency response planning and allow assessment of downstream mitigation options.

Rain-on-grid modelling
RoG modelling is a hydrological simulation technique that evaluates the interactions between precipitation and TSF surfaces. By generating synthetic rainfall events over a digital terrain model, RoG can simulate runoff, infiltration, and erosion processes (Hancock *et al*., 2008).

For example, Figure 3 illustrates how an intense rain event can cause pools to build up in the paddocks on the TSF basin and the associated flow vectors, which are then drawn down using the spillway, highlighting areas that may require additional armouring or energy dissipaters. This allows technical concepts to be simply illustrated and consequently facilitate 'meaningful engagement', in GISTM terms.

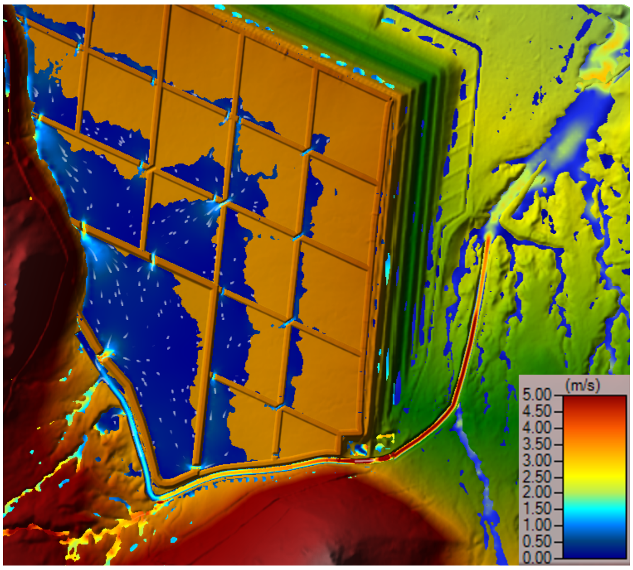

Figure 3. Spatial velocity and flow vectors map from RoG modelling (Van der Colf et al. *2024).*

Landform evolution modelling
LEM is used to predict long-term morphological changes in landscapes. It employs computational algorithms to simulate erosion, sediment transport, and vegetation growth over extended time periods (Hancock *et al*., 2008). This technique provides a visual understanding of how a TSF and its surrounding landscape will evolve, enabling the design of stable and aesthetically pleasing post-mining landforms. By incorporating LEM into closure planning, engineers can create robust rehabilitated landscapes that support ecological restoration and biodiversity (Evans *et al*., 2015). An example of LEM for a TSF closure design is provided below in Figure 4, where the cool and warm colours respectively indicate deposition erosion depths.

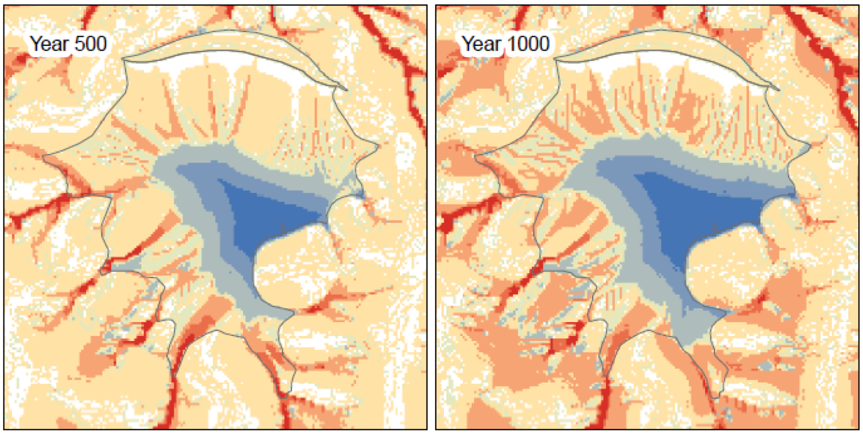

Figure 4. LEM results (Thomson & Chandler, 2019).

Rendered images and videos
Rendered images and videos are powerful tools for visualising and communicating technical data to a wide range of stakeholders. These visualisations create lifelike representations of proposed closure designs, helping stakeholders understand the planned rehabilitation activities (Langridge *et al.,* 2014). Advanced technologies such as virtual reality and augmented reality can enhance these visualisations by providing immersive experiences that allow users to explore and interact with virtual models of TSF landscapes. By fostering stakeholder engagement and informed decision-making, these tools support more effective closure planning (Murphy & Cooney, 2014).

Learning from nature
Learning from nature involves emulating natural processes and systems in the closure and rehabilitation of TSFs. This approach includes promoting soil and topsoil formation through natural weathering and incorporating organic matter, using biodiverse systems to enhance resilience, and incorporating redundancy to mitigate risks (Ollerer, 2015). A recent study demonstrated that converting tailings to soil using microbes can significantly enhance nitrogen-rich organic matter formation and stabilisation, offering a promising approach for ecological rehabilitation of TSFs (Wu *et al.*, 2023).

By drawing inspiration from ecological principles, engineers can develop closure strategies that foster habitat creation, improve soil health, support biodiversity and potentially even support regeneration of the site. This biomimetic approach not only enhances the ecological sustainability of TSFs but also contributes to the long-term stability and resilience of rehabilitated landscapes (Bergen *et al.*, 2001).

ECOLOGICAL AND SOCIOLOGICAL INTEGRATION

The sustainable closure of TSFs requires a holistic approach that integrates both ecological and sociocultural considerations to ensure long-term success and acceptance of closure plans, as schematically shown in Figure 5.

Importance of integrating ecological and sociocultural considerations
Integrating ecological and sociocultural considerations into TSF closure plans is crucial for ensuring that these landscapes can support biodiversity, ecosystem services, and community well-being. Ecologically, the restoration of natural habitats and the promotion of biodiversity are essential for creating resilient ecosystems that can adapt to environmental changes. Sociocultural considerations involve engaging local communities in the closure planning process, understanding their needs and addressing their concerns. Doing so not only fosters community support but also ensures that post-closure land uses provide tangible benefits, such as recreational spaces or agricultural lands that enhance the quality of life for nearby residents (Franks *et al.*, 2011). This integration promotes a symbiotic relationship between the natural environment and local communities, leading to more sustainable and accepted outcomes.

Alignment with ESGS goals

Aligning TSF closure plans with ESGS goals is a strategic approach that ensures the long-term sustainability and corporate responsibility of mining operations. ESGS frameworks emphasise the need for environmental stewardship, social equity, and robust governance, all of which are critical for achieving sustainable closure outcomes. Ecologically, this means implementing practices that restore and preserve natural habitats, manage water resources effectively, and minimise the environmental footprint of TSFs. From a social perspective, this involves actively engaging with stakeholders, ensuring equitable access to resources, and fostering social cohesion through community-driven initiatives. Governance and sustainability aspects focus on transparency, accountability, and the continuous improvement of closure strategies based on regular monitoring and feedback (ICMM, 2021). By aligning with ESGS goals, mining companies can demonstrate their commitment to responsible practices, mitigate long-term risks, and contribute to broader sustainable development objectives (Brundtland Commission, 1987).

Figure 5. Combining ecological restoration with sociocultural benefits for mine closure planning (image generated using Microsoft Designer).

CASE STUDIES AND EXAMPLES

Examining real-world case studies and examples of successful TSF closures provides valuable insights into best practices and the lessons learned from various projects. These case studies highlight the strategies and approaches that have been effective in achieving sustainable closures, offering guidance for future initiatives.

Examples of successful TSF closures

Example 1: Waihi Gold Mine, New Zealand

The closure of the Waihi gold mine's TSF involved extensive stakeholder engagement and advanced ecological restoration techniques. The site was transformed into a community park with native vegetation, walking trails, and water features, providing both environmental and recreational benefits. The rehabilitation process included land reshaping, topsoil application, and planting native species, resulting in improved biodiversity and a valued community asset (GENIVAR, 2011).

Example 2: Lisheen Mine, Ireland

The closure of the Lisheen mine in Ireland is a notable example of effective TSF rehabilitation. The closure plan included the stabilisation of tailings, capping with topsoil, and the creation of wetland areas to enhance biodiversity. Continuous monitoring and local community involvement ensured that the site was transformed into a sustainable land use, benefiting both the environment and the local population (Department of Communications, Climate Action and Environment, 2015).

Example 3: Browns Range Rare Earths Project, Australia
The closure of the Browns Range Rare Earths TSF involved employing geomorphic design principles to create landforms that mimic natural landscapes. This approach promoted long-term stability and minimised environmental impacts. Ongoing monitoring and adaptive management ensured the integration of the TSFs into the natural environment, enhancing biodiversity and ecosystem function post-closure (Webster *et a*l., 2009; Evans *et al*., 2015; Hancock *et al*., 2008).

Lessons learned and best practices
Several key lessons and best practices have emerged from these successful closures, providing guidance for future TSF closure projects:

1. **Early planning and integration**: Initiating closure plans early in the TSF lifecycle allows for the integration of sustainable practices from the outset. This proactive approach ensures that environmental and social considerations are embedded in the design and operation stages, leading to more successful closures (Mudd, 2010).
2. **Stakeholder engagement**: Engaging with local communities, regulators, and other stakeholders throughout the closure process is crucial for fostering support and addressing concerns. Transparent communication and collaboration help build trust and ensure that the closure plan aligns with the needs and expectations of all parties involved (Franks *et al*., 2011).
3. **Adaptive management**: Implementing adaptive management practices enables continuous improvement based on monitoring and feedback. This flexibility allows for adjustments to be made as new information emerges, ensuring that the closure plan remains effective over time (McCullough and Lund, 2006).
4. **Innovative engineering and ecological techniques**: Using advanced engineering methods and ecological restoration techniques can enhance the stability and sustainability of TSF closures. Practices such as landform redesign, revegetation with native species, and the creation of wetlands contribute to the long-term success of rehabilitation efforts (Evans *et al*., 2015).
5. **Socio-economic development**: Integrating socio-economic development initiatives into closure plans can provide lasting benefits for local communities. Projects that create alternative livelihoods, such as sustainable agriculture or recreational areas, contribute to the overall well-being and economic resilience of the affected regions (Murphy & Cooney, 2014).

CONCLUSION

The challenging but crucial process of TSF closure from the perspective of sustainability and stakeholder engagement has been explored. The closure of TSFs presents significant environmental, social, governance, and economic challenges that require a holistic and forward-thinking approach. By reverse engineering TSFs to incorporate closure planning from the earliest stages of the facility's lifecycle, it is possible to minimise environmental footprints and enhance ecological regeneration and socio-economic benefits.

A critical aspect of sustainable TSF closure lies in stakeholder engagement. Tailings engineers, owners, regulators, local communities, and ecosystems all have a vested interest in the successful closure of these facilities. Advanced tools and modelling techniques, including dam breach assessments, rain-on-grid modelling, landform evolution modelling, and rendered images and videos, contribute significantly to bridging the gap between technical complexities and stakeholder understanding. These tools validate design assumptions, predict long-term performance, and visually communicate potential outcomes to non-technical audiences.

The integration of ecological and sociocultural considerations is essential in designing closure strategies that align with broader ESGS goals. By learning from nature and applying biomimetic principles, engineers can develop strategies that foster ecological balance, biodiversity, and resilient ecosystems. Sociocultural considerations ensure that closure plans provide tangible benefits to local communities, enhancing their quality of life through the creation of recreational spaces, agricultural lands, or wildlife reserves.

Successful case studies, such as the closure efforts at the Waihi gold mine, Lisheen mine, and Browns Range Rare Earths Project, demonstrate the efficacy of early planning, stakeholder engagement, adaptive management, innovative engineering, and ecological techniques. These examples provide valuable insights and best practices that can guide future TSF closure projects towards more sustainable and resilient outcomes.

Moving forward, it is recommended that mining companies adopt a proactive approach to TSF closure, integrating closure planning into the design and operational phases of their facilities. Continuous monitoring, adaptive management, and inclusive stakeholder engagement should form the cornerstone of TSF management practices. By aligning closure strategies with ESGS goals, the mining industry can contribute to sustainable development and the revitalisation of post-mining landscapes, thereby ensuring a positive legacy for future generations.

In conclusion, the sustainable closure of TSFs is not only a technical challenge but a responsibility that requires a collaborative and innovative approach. By embedding sustainability into the heart of TSF design and operation, and leveraging advanced tools and holistic strategies, the mining sector can achieve closures that respect and rejuvenate the environment while delivering extensive benefits to local communities and stakeholders.

REFERENCES

Bergen, S.D., Bolton, S.M. and Fridley, J.L. (2001). Design principles for ecological engineering. Ecological Engineering, 18(2), pp. 201–210.

Blight, G.E. (2010). Geotechnical engineering for mine waste storage facilities. CRC Press.

Brundtland Commission. (1987). Our Common Future. Oxford University Press.

Department of Communications, Climate Action and Environment. (2015). The Lisheen Mine Closure Plan. Available at: https://www.dccae.gov.ie Accessed 12 August 2024.

Environmental Agency. (2004). Improving the Ecological Sustainability of Mine Rehabilitation Projects. Environmental Agency Publications.

EPA. (1994). Technical Report: Tailings Management for Stable, Sustainable Rehabilitation. Environmental Protection Agency.

Evans, G., Hancock, G., Saynor, M. and Loch, R. (2015). Field assessment of a landform evolution model: application to trial rehabilitated tailings dams. Geomorphology, 241, pp. 164–176.

Franks, D.M., Brereton, D., Moran, C.J., Sarker, T. and Cohen, T. (2011). Cumulative impacts—a good practice guide for the Australian coal mining industry. Centre for Social Responsibility in Mining.

GENIVAR. (2011). Waihi Gold Mine Closure Plan. Available at: https://www.waihigold.com/assets/general-documents Accessed 12 August 2024.

ICMM. (2020). The Global Industry Standard on Tailings Management. ICMM (International Council on Mining and Metals), London.

ICMM. (2021). Tailings Management: Good Practice Guide. International Council on Mining and Metals.

Hancock, G.R., Turley, E., Evans, K.G. and De Silva, H. (2008). Rehabilitation assessment using landform evolution models for sloping terrain in the northern coalfields of New South Wales, Australia. Australian Journal of Soil Research, 46(1), pp. 28–37.

Langridge, R., Fram, M.S., and Fisher, A.T. (2014). Groundwater in the balance. Science, 346(6208), pp. 818–819.

Lottermoser, B.G. (2011). Mine Wastes: Characterization, Treatment and Environmental Impacts. Springer Science & Business Media.

Mackenzie, B. (2011). Sustainable Mine Rehabilitation. Environmental Management Series.

McCullough, C.D. and Lund, M.A. (2006). Opportunities for sustainable mining pit lakes in Australia. Mine Water and the Environment, 25(4), pp. 220–226.

Morrison, K., Genrich, R., Trimble, B. and Bagge, A. (2007). Closure of the Waihi Tailings Storage Facility in New Zealand. Proceedings of the 2007 International Mining Conference.

Morrison-Saunders, A., Arts, J., and Caldwell, P. (2008). Environmental Impact Assessment Follow-up: Good Practice and Future Directions. Routledge.

Morris, G. and Binns, F. (2011). Environmental management of mine sites at closure – some insights. Minerals & Energy-Raw Materials Report, 16(2), pp. 3–13.

Mudd, G.M. (2010). The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resources Policy, 35(2), pp. 98–115.

Murphy, D. and Cooney, M. (2014). Ecological and Social Considerations in the Rehabilitation of Tailings Storage Facilities. Journal of Environmental Management.

Ollerer, K. (2015). Bioremediation and the restoration of biodiversity on mining landscapes in the Apuseni Mountains Europe. Natura Montenegrina, 14(2), pp. 109–125.

Owen, J.R. and Kemp, D. (2013). Social licence and mining: A critical perspective. Resources Policy, 38(1), pp. 29–35.

Paterson, A. and Dormuth, R. (2011). Tailings Management: The Regulator's Perspective. Tailings and Mine Waste.

Sheoran, A.S., Sheoran, V. and Poonia, P. (2010). Rehabilitation of mine degraded land by metallophytes. Mining Engineers' Journal, 12(2), pp. 30–34.

Thomson, H. and Chandler, L. (2019). Tailings storage facility landform evolution modelling. In: Fourie, A.B. and Tibbett, M. (eds), Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 385–396, https://doi.org/10.36487/ACG_rep/1915_31_Thomson

Van der Colf, R.P., Bolton, C.R., Ilott, I.R. and Walls, J.M. (2024). Integrating rain-on-grid modelling to enhance the development of tailings storage facility surface water closure plans. In: Symposium "Dams for People, Water and Environment and Development" - 92nd ICOLD Annual Meeting, ICOLD, New Delhi (In press).

Webster, R., Pollino, C. and Webb, J.A. (2009). A framework for developing geomorphic design criteria for high-risk tailings storage facilities. Environmental Geology, 58(5), pp. 1073–1081.

Wu, S., Bougoure, J., Wang, J., Thomsen, L., Chan, T.S., Yi, Q., Li, Z., Southam, G. and Huang, L. (2023). Nitrogen-Rich Organic Matter Formation and Stabilization in Iron Ore Tailings: A Submicrometer Investigation. Environmental Science & Technology, 57(33), pp. 12325–12338.

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Water stewardship at Kumba Iron Ore

T. White[1], N. Mkhize[2], and G. McGavigan[2]

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Kumba plays a vital role in regional water security for the Northern Cape Province. The surplus groundwater produced via the active mine dewatering systems at Sishen and Kolomela is supplied to the regional water supply scheme and the Gamagara Local Municipality. This water is of high quality, requiring minimal treatment and supports residents and industry between Postmasburg and Black Rock. As a responsible water steward, Kumba takes this role very seriously and has applied concerted efforts and rigour in developing strategies, plans and standards that align with international best practice. A revised water management strategy for Kumba was developed in 2024. The new strategy incorporates the International Council of Mining and Metals Water Stewardship Framework, the Initiative for Responsible Mining Assurance standard and the relevant Anglo American technical standards, guidelines, frameworks and processes. The strategy details four key focus areas; increasing predictive capabilities, adaptive water management, stabilisation of dewatering networks and optimisation of dewatering distribution systems. Principles that Kumba applies in support of the four strategic elements are strategic dewatering, proactive surface water management, hierarchy of use and diversions for beneficial use. The execution of this comprehensive strategy will enable Kumba to empower its water stakeholders through meaningful engagement and ensure the beneficial use of Kumba's water resources for all. In this paper, we present the rationale behind the development of Kumba's water management strategy and some examples of how it is applied in practice.

Keywords: water stewardship, mine dewatering, beneficial use, adaptive water management, water security, hierarchy of use

INTRODUCTION

Kumba's mining operations in the Northern Cape, Sishen and Kolomela, are two of the largest active dewatering operations globally. Each mine abstracts groundwater from the underlying dolomitic and banded ironstone aquifers at rates between 1500 and 2000 m^3/h to facilitate dry mining conditions. Active dewatering is a critical enabler for successful mining of these premium iron ore deposits and primarily supports pit slope stability and efficient production. Dry mining conditions in large open pits are required for pit slope stability, efficient drill, blast, load and haul as well as and safe working conditions (roads, housekeeping, bench conditions). The necessity for active dewatering in a water scarce area may seem paradoxical but both mines are underlain by the Malmani dolomites which form the primary aquifer for the region due to the fractured and karstic features of the dolomite. Through the process of active dewatering, Kumba generates more water than it requires for their own use and approximately 70% of the groundwater abstracted is supplied to the regional water scheme (Vaal Gamagara Water Supply Scheme), shown in Figures 1 and 2 and the Gamagara Local Municipality. This water forms the second largest water resource in the Northern Cape Province after the Orange and Vaal river systems and can support ~200 000 people with high quality water.

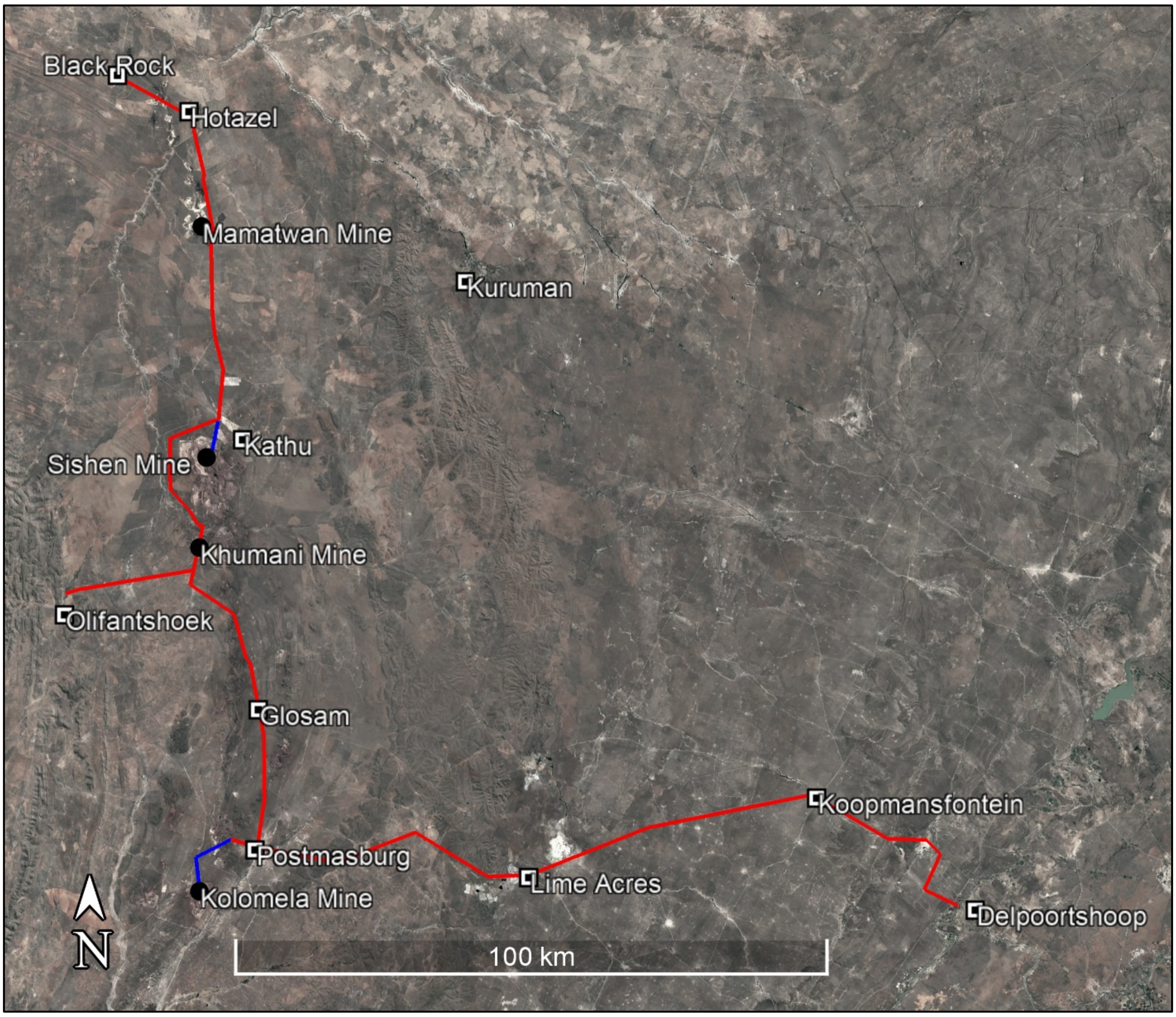

Figure 1. Vaal Gamagara water supply scheme from Delpoortshoop to Black Rock (red) with Sishen and Kolomela tie-ins (blue).

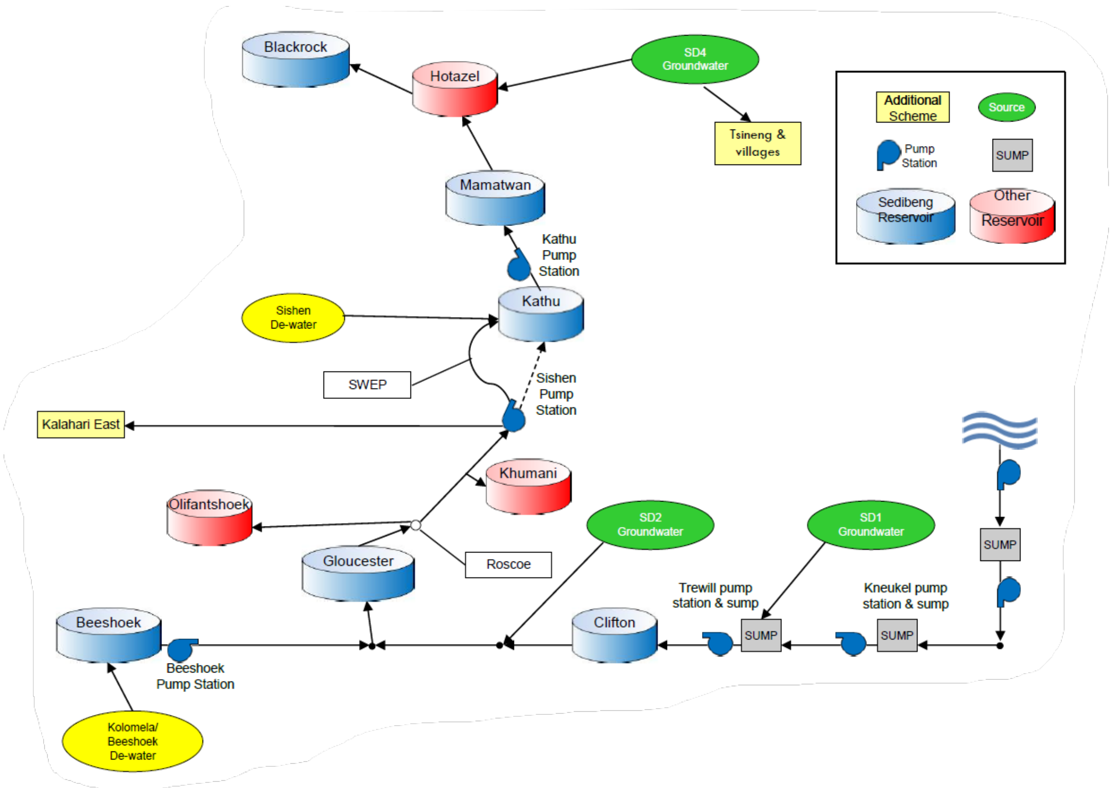

Figure 2. Schematic layout of Vaal Gamagara Water Supply Scheme (Deysel, 2019).

Kumba has realised the important role it plays in the regional water setting, which has driven Kumba's commitment to being a responsible water steward and an active leader in water stewardship for the region. Kumba's recently obtained Initiative for Responsible Mining Assurance (IRMA)75 accreditation is proof of this commitment and is where Kumba's adaptive water management approach has been recognised as part of the accreditation process. Through collaborative and proactive identification of potential current and future water challenges and the development of adequate, adaptable management strategies throughout the mining life cycle, Kumba has been able to minimise, or prevent altogether, impacts on water quality and quantity in the receiving environment. Through Kumba's purpose, goal and water management vision, shown in Figure 3, adaptive and responsible water management has become the 'business as usual' case at the operations.

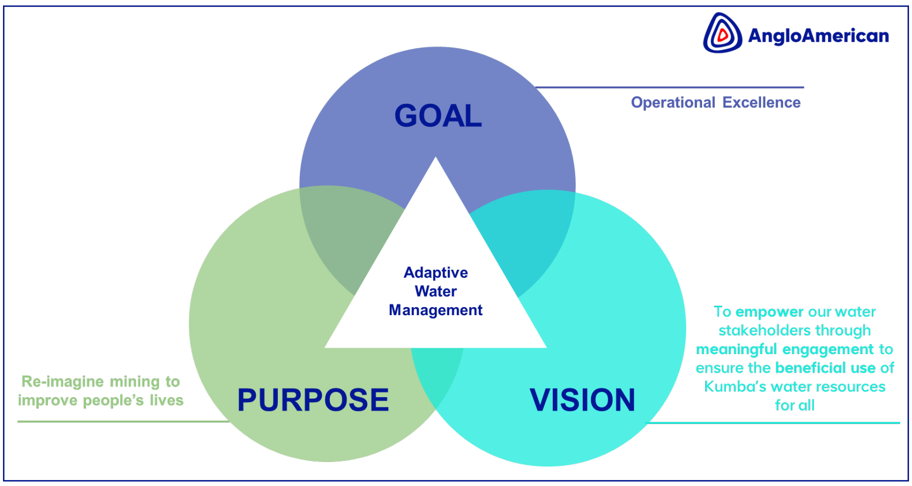

Figure 3. Adaptive water management in the context of Kumba and Anglo American's goal, vision and purpose (Damhuis, 2023).

Given the importance of this resource to the region and Kumba's commitment to being a responsible water steward, Kumba has put a concerted effort into developing a water management strategy that aligns with global best practices, frameworks, guidelines and mandates. This approach includes effective water management at the operations, allowing for safe, sustainable and continuous mining to take place, as well as transparent and regular stakeholder engagement, both internally and externally, to inform decision-making within the water management systems. In this paper, we present Kumba's approach to water management with water stewardship at its core, examples of how water stewardship is applied at the operations and the benefit to the region.

The ICMM Water Stewardship Framework

Anglo American and Kumba are members of the International Council of Mining and Metals (ICMM) and are committed to the ICMM principles and performance expectations. The ICMM have defined a 'Water Stewardship Framework' that covers four strategic imperatives:

1. *Be transparent and accountable* – "Publicly report material water risks, management activities and performance."
2. *Engage proactively and inclusively* – "Engage stakeholders in an open and transparent manner to understand their priorities, share plans and collaborate on solutions."
3. *Adopt a catchment-based approach* – "Understand the social, cultural, economic and environmental value of water at the catchment scale to identify material water stewardship risks and provide context for corporate and operational water management."
4. *Effective water resource management* – "Manage operational water (quantity and quality) inputs, use and outputs to maximise resource sustainability, operational flexibility and economic benefit."

Kumba have incorporated these strategic imperatives into their water management strategy and apply them as follows:

- publicly report all water data as part of the Anglo American corporate water reporting mandate,
- actively engage with all its stakeholders and host various forums,
- have a well-defined position and role within the catchment and sound understanding of impact (positive and negative), and
- apply best practice principles for both water quality and quantity.

Kumba's Water Management Strategy

Kumba developed a revised water management strategy (Damhuis, 2024) with a strong focus on water stewardship. The purpose of the revised Kumba water strategy is to enable Anglo American's vision to 're-imagine mining to improve people's lives' and is aligned with the Anglo American Sustainable Mining Plan (SMP) objectives. There are three global sustainability pillars within the SMP: healthy environment, thriving communities and trusted corporate leader. Water management falls within the healthy environment pillar but water also plays a vital role in the remaining two pillars. Over and above the Anglo American vision, SMP and focus on water stewardship, the Kumba water strategy incorporates several internal policies, programmes, frameworks and standards such as the Anglo American operating model; operational risk management process; group technical standards; safety, health, environment (SHE) Way and Social Way. All the elements above were used to derive a new vision for water management at Kumba that is aligned with the guiding principles of sustainable mining, Anglo American's internal protocols and the ICMM strategic imperatives. The Kumba water management vision is presented in Figure 4 below:

To empower our water stakeholders through meaningful engagement to ensure the beneficial use of Kumba’s water resources for all

Figure 1. Kumba's water management strategy vision.

Kumba water management strategy elements

In the process of developing Kumba’s revised water management strategy, a strength, weakness, opportunity, and threat (SWOT) analysis was conducted to take stock of the status quo and ensure that the strategy developed spoke to all aspects of water management. Through the SWOT analysis, four strategic elements were identified that, if effectively implemented, would enable the realisation of Kumba’s water management strategy vision.

Increased predictive capabilities

Improving the predictive capabilities within the water management discipline at Kumba’s operations is an enabler to achieving the vision of empowering stakeholders through meaningful engagement and ensuring beneficial use of water resources for all. This is enabled by being better informed when making water management decisions and empowering the accountable teams to implement, adapt and execute responsibilities to enable stable operations. The key focus areas for predictive capability improvements are water balance modelling, hydrogeological modelling, and operational system hydraulic modelling (water infrastructure).

Adaptive water management

The IRMA requires mining operations to have adaptive water management plans. Adaptive water management, within the context of IRMA’s requirements, entails defining, in advance, the actions required to address predicted changes to water quality and quantity through appropriate mitigation measures. This links to the strategic element above on improving predictive capabilities and the following points have been considered in the context of applying adaptive water management at Kumba:

- Monitoring requirements and entities per water system component
- Data analysis techniques applied to monitoring data
- Predictive tools and their frequency of use
- Reporting, presentation and communication of results
- Decision-making process and management of change when adaption is required, and
- Record keeping of monitoring results and decisions for change.

Kumba has drafted an adaptive water management standard (Damhuis, 2023) which will be implemented at both operations to improve their resilience.

Stabilisation of dewatering networks at operations
Sishen and Kolomela have set groundwater level targets at two benches (between 20 m and 25 m) below the lowest mining level at any given point in time. This is achieved through the implementation of active dewatering and entails the use of large diameter (>330 mm) boreholes drilled to depths in excess of 300 metres below surface and equipped with submersible electric pumps. Kumba has faced some challenges in achieving its required dewatering rate due to downstream capacity constraints on the regional and municipal water networks. These constraints put pressure on the dewatering networks, resulting in suboptimal performance. It is for this reason that focus on stabilisation of the dewatering networks is necessary to enable successful execution of the business plan and, due to the role Kumba plays in the region with respect to water provision, ensure beneficial use of Kumba's resources for all.

Stabilisation of dewatering networks will be achieved through effective maintenance and engineering availability. This covers maintenance of critical spares stock levels, regular inspections and performance monitoring and applying the necessary technical rigour during solution design.

Optimisation of dewatering distribution at operations
The conveyance and distribution of water at Kumba's operations plays a critical role in both effective dewatering and third-party water supply (diversions). There are discrete systems for clean (groundwater) and contact (stormwater, treated sewage effluent, process water, return water etc.,) water. Kumba has invested over R1.8 billion in water infrastructure at its operations over the last decade but, due to the dynamic nature of mining, there is always room for improvement and optimisation. Through optimisation of dewatering distribution networks, Kumba can operate in a more stable condition which will enable downstream benefits to third-party stakeholders. This can be achieved through hydraulic modelling of the current water distribution network in its entirety and testing various scenarios to determine water balance impacts and physical limitations on the existing system, which will highlight opportunities for improvement that can then be actioned. These actions include reconfiguration of existing pump stations, additional storage, pipeline upgrades, implementation of new technologies and expansion of the telemetry system.

Strategic dewatering and implementation plans
Sishen started dewatering in the mid 1970s and Kolomela in 2008. Kumba developed strategic dewatering and implementation plans based on the Guidelines for evaluating water in pit slope stability by Beale and Read (2014) which forms part of the series of publications through the Large Open Pit Project. Anglo American, in collaboration with Kumba, then developed its own internal guide called 'Strategic Dewatering Plan: development and implementation framework' which provides detailed guidance for Anglo American operations on how mine dewatering and depressurisation programmes should be established. This framework is based on the success of Kumba's mine dewatering programmes and laid the blueprint for other Anglo American operations to follow. There are six key work steps in the development and implementation of a strategic dewatering plan. These six steps and the workflow are presented in Figure 5.

Development of a dewatering strategy will normally include six steps

STEP 1: Screening-level assessment

- Assessment of the required scale of the program
- Planning of the required resources

STEP 2: Characterization of the geological and hydrological conditions

- District scale
- Site Scale

STEP 3: Development of a conceptual model and strategic planning

- Development of the overall water management strategy, including dewatering options and trade-off analysis
- Preparation of the terms of reference (ToR) and budgets for the 5 year (5YP) and life of asset plan (LOAP) planning cycles

STEP 4: Mine dewatering system design

- Analytical and/or numerical supporting analysis
- Assessment of risks

STEP 5: Implementation

- Progressive installation of the system based on the mine plan (LOAP)
- Interactive adjustment based on the on-going monitoring results
- Definition of staff, roles and organizational structure

STEP 6: Monitoring and reporting

- Feedback loop to optimize the implementation
- Strategy and implementation review by stakeholders and experts

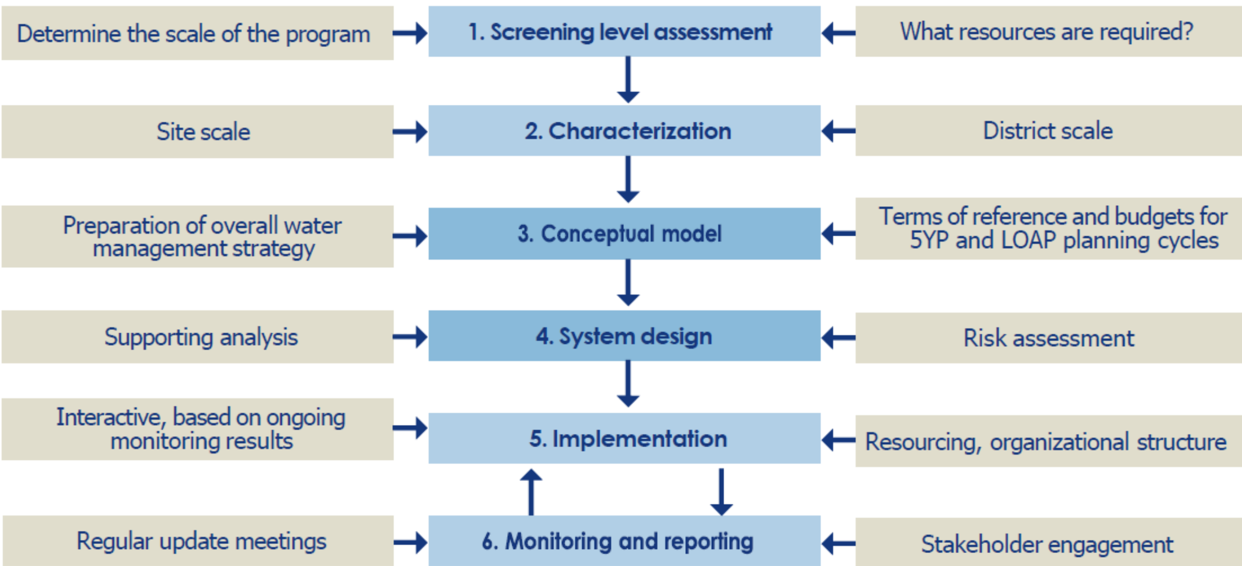

Figure 2. The six work steps in the development of a dewatering strategy (Anglo American, 2024).

Adaptive Water Management

On the back of the IRMA requirement to have an adaptive water management plan in place and above average rainfall at Sishen in 2021, the Kumba water management team formulated the 'rainfall readiness plan'. This is a global best practice body of work that has further been developed into a standard for proactive surface water management in Anglo American (Damhuis, 2023).

Proactive surface water management: rainfall readiness plan

The key driver in developing a standard for proactive surface water management was to ensure the continued safety of all persons on site, protect the business plan and ensure that operations are adequately equipped to respond to meteorological events and the ever-increasing pressures of climate change. At its core, this standard focuses on integrating the physical requirements of proactive surface water management into existing work management processes to ensure adoption and effective execution of the rainfall readiness plan. The proactive water management standard is fully aligned with Anglo American procedures, standards and frameworks and addresses the diverse mining methods, climatological settings, and operational constraints across the portfolio.

Like the strategic dewatering plan development and implementation framework, proactive surface water management and rainfall readiness plan development includes six steps as shown in Figure 6 and discussed below:

- **Step 1**: Use the guiding principles, based on operational excellence characteristics, to define a clear vision and strategic objectives.
- **Step 2**: Set the business expectations following a source-pathway-receptor model where the source is the origin of the risk to the receptor, the pathway is the method of the receptor being exposed to the risk and receptor is the impacted stakeholder, equipment or process.
- **Step 3**: Commence operational planning to ensure work is planned, scheduled, and resourced adequately, as per the Anglo American operating model, to enable the "right work to take place at the right time and completed in the right way".
- **Step 4**: Work management which includes detailed tracking and reporting on the tasks linked to the successful execution of the rainfall readiness plan before and during the rainy season.
- **Step 5**: Feedback and communication that ensures maintained alignment with the objectives and vision developed by the operation in step 1. This is a crucial step because the intention of feedback is to enable adaptability in managing dynamic surface water effectively and empower the various teams and stakeholders involved to contribute towards the overarching objectives and vision for the operation and willingly accept accountability for their respective tasks in the overall process of proactive surface water management (maintain consistent narrative).
- **Step 6**: Performance monitoring where improvements, or deterioration, on overall system vulnerability are tracked and reported weekly.

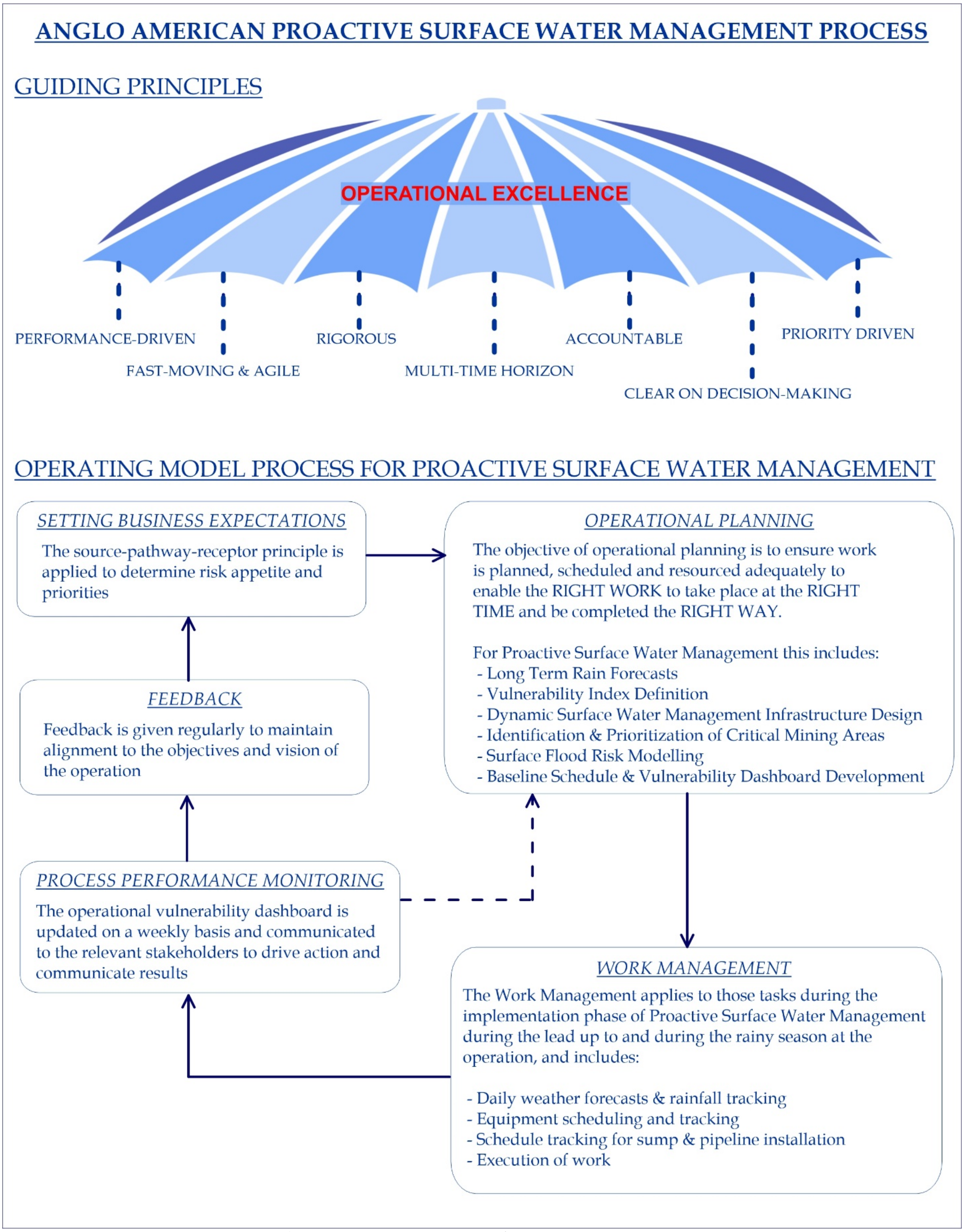

Figure 3. Anglo American proactive surface water management process.

Applying water stewardship principles at Kumba

Hierarchy of use

Kumba applies hierarchy of use and a *fit-for-purpose* philosophy to water consumption on site. This entails prioritising the use of lower quality water over higher quality water and maintaining freeboard levels in dams to optimally manage water distribution on site. This practice is particularly relevant at Sishen mine which has access to multiple water sources. Sishen's hierarchy of use is applied as follows:

1. Return water from the tailings storage facility.
2. Treated sewage effluent from the Kathu wastewater treatment works.
3. Recovered stormwater from the pollution control dams and stormwater sumps.
4. Groundwater from the mine dewatering network.

Applying hierarchy of use means that Kumba can increase the volumes of high-quality water available from the mine dewatering system to divert for beneficial use. The use of treated sewage effluent at Sishen also assists the local municipality by eliminating the need for additional treatment and the potential negative impacts to the environment if the water was otherwise discharged. There are several examples within South Africa of the negative impact of treated sewage effluent discharge to water ecosystems, and particularly within the Northern Cape context, this would be exacerbated due to the low mean annual precipitation and scarcity of perennial riverine systems.

Beneficial use (diversions)

Since Kumba's operations produce more water than they require for their own needs, they are considered water-positive mines. This is a unique position given that both operations are in water-scarce areas. The surplus water generated through active mine dewatering is exported offsite to two key entities for human consumption; the Vaal Gamagara Water Supply Scheme (VGWSS) operated by Vaal Central and the Gamagara Local Municipality (GLM) which services the towns of Kathu, Deben and Olifantshoek. The VGWSS starts at Delpoortshoop on the Vaal river and ends at Black Rock which is approximately 80 km north of Sishen mine. The water from Sishen and Kolomela is distributed to residential and industry users between Postmasburg and Black Rock via the VGWSS. The GLM receives water directly from Sishen mine and supplies water to the residents of Kathu, Sesheng and Mapoteng.

There are times when the third-party stakeholders are not able to take the full surplus water volumes from the mines so Kumba has invested in developing managed aquifer recharge (MAR) systems at both operations. The two sites for MAR are the Groenwaterspruit and Khai-Appel aquifers at Kolomela and Sishen respectively. MAR entails injecting water back underground in a controlled manner through recharge boreholes where the aquifer stores the water for later use. This practice ensures long term aquifer sustainability and reduces water losses, such as evaporation and evapotranspiration, which occur at high rates in surface water bodies (dams or lakes). MAR systems reduce the risk of surface discharge of groundwater when third parties cannot accommodate the surplus volumes.

Khumani mine, which neighbours Sishen, is the largest water user on the VGWSS. Sishen has an extensive stormwater management infrastructure network and has collaborated with its neighbour by establishing the Sishen-Khumani Water Transfer agreement. Sishen pumps reclaimed stormwater from its pits and stormwater sumps to Khumani that reduces the volumes of water pulled from the VGWSS by Khumani and increases the availability of water for human consumption. This is an excellent example of beneficial use, application of fit for purpose water use and collaboration between competitors that benefits all stakeholders.

The water exported by Kumba is classified as a 'diversion' or 'other managed water' as per the ICMM and Water Accounting Framework definitions. The total volumes diverted from site by Sishen and Kolomela combined for beneficial use are presented in Figure 7.

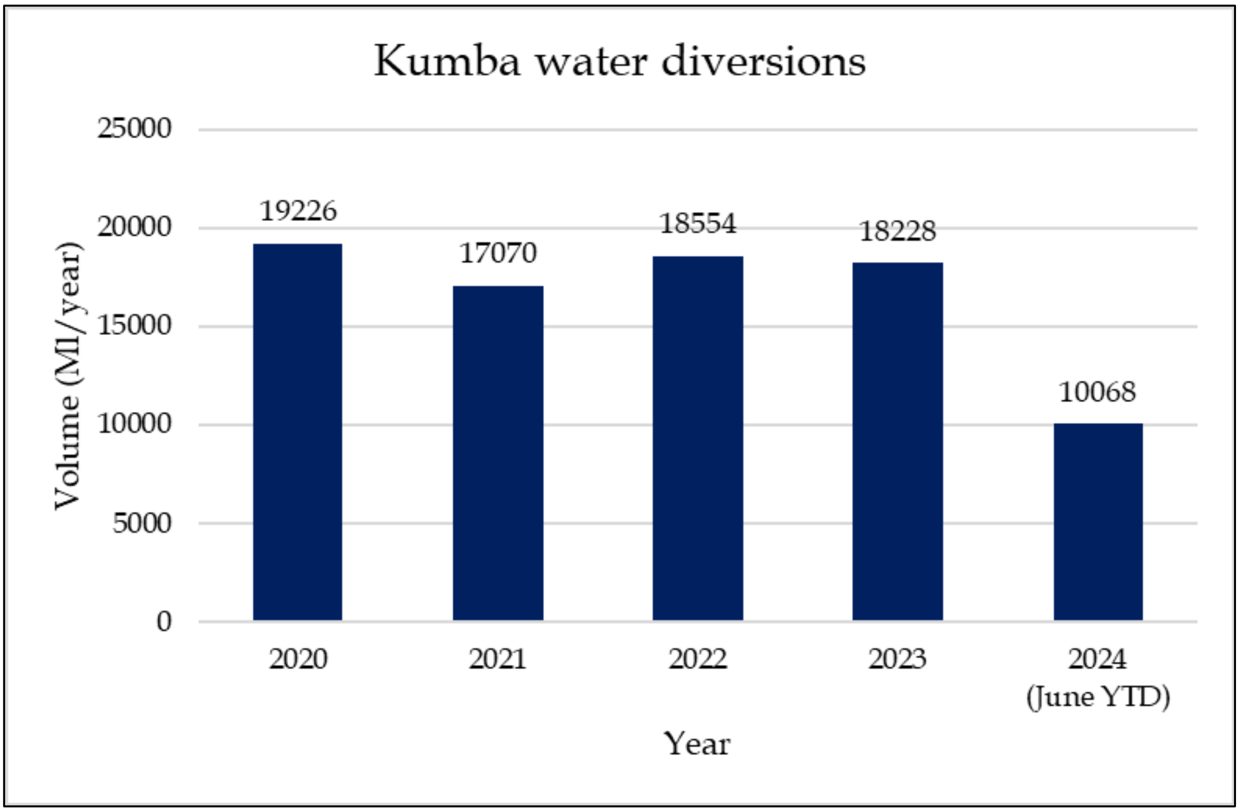

Figure 7. Kumba annual water diversion volumes for beneficial use.

CONCLUSION

Sishen and Kolomela play crucial roles in water supply for the region and Kumba takes this very seriously. Kumba is committed to being a responsible water steward and there are active endeavours underway to further improve. A substantial effort has gone into developing the guidelines, strategies, standards and procedures that govern water management and ensuring that these are aligned with international best practices. The principles of adaptive water management are a thread throughout the way Kumba goes about business and this reflects in their achievements. The execution of the new water management strategy will take Kumba to new heights and guarantee the vision of empowering its water stakeholders through meaningful engagement to ensure the beneficial use of Kumba's resources for all is realised.

REFERENCES

Anglo American (2024). Group Technical Standards, Water Management Standard, AA TS 033 Version 5. Johannesburg, South Africa, 12 pp.

Anglo American (2023). Strategic Dewatering Plan: development and implementation framework. Anglo American, Johannesburg, Gauteng, South Africa. 52 pp.

Anglo American Sustainable Mining Plan, https://www.angloamerican.com/sustainable-mining-plan [accessed 30 Jun. 2023].

Anglo American operating model, Anglo American Operating Model (sharepoint.com) [accessed 12 Mar. 2022].

Anglo American operational risk management process, Operational Risk Incident Management Guidelines (Final).docx (sharepoint.com) [accessed 12 Mar. 2022].

Anglo American SHE way (safety, health, environment), SHE - She way - Home (sharepoint.com) [accessed 12 Mar. 2022].

Anglo American Social Way, Social Way - Home (sharepoint.com) [accessed 12 Mar. 2022].

Beale, G. and Read, J. (2014). *Guidelines for evaluating water in pit slope stability,* CSIRO publishing, Clayton, Australia.

Damhuis, M.J. (2024). Kumba water management strategy. Anglo American, Kumba Iron Ore, Johannesburg, Gauteng, South Africa. 33 pp.

Damhuis, M.J. (2023). Kumba Iron Ore Adaptive Water Management Standard. Anglo American, Kumba Iron Ore, Johannesburg, Gauteng, South Africa. 40 pp.

Damhuis, M.J. (2023). Proactive surface water management: design, implementation and maintenance standard. Anglo American, Johannesburg, Gauteng, South Africa. 33 pp.

Deysel, E. (2019). Vaal Gamagara Water Supply Scheme: Updated demographics and water balance to 2043. iX Engineers for Pro-Plan, Kimberley, South Africa. 79 pp.

ICMM water stewardship framework (2014). https://www.icmm.com/en-gb/guidance/environmental-stewardship/2014/water-stewardship [accessed 30 Mar. 2022].

Initiative for Responsible Mining Assurance (IRMA) (2018). The Standard for Responsible Mining. [online] Initiative for Responsible Mining Assurance. Available at: https://responsiblemining.net/resources/#full-documentation-andguidance [Accessed 10 Nov. 2022].

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The role of artisanal and small-scale mining in poverty alleviation and rural development

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Artisanal and small-scale mining (ASM) plays a significant role in many communities worldwide, where formal employment opportunities are limited (Hentschel, Hruschka, and Priester, 2002). The sector is not without its challenges: environmental degradation, health and safety risks, and inadequate infrastructure are significant concerns that must be addressed to ensure sustainability (Hilson, 2002). This paper explores the multifaceted impact of ASM on social communities, considering both positive and negative dimensions. A key point of this study is the potential of ASM to empower marginalised groups such as women, people with disabilities, and youth – leading to economic empowerment and poverty alleviation (Buxton, 2013). Additionally, revenue generated from formalised ASM activities often stays within local communities, supporting small businesses and stimulating local economies (Hilson and McQuilken, 2014). The ASM policy gazetted by the South African government is a testament to the sector's potential to thrive and contribute significantly to the economy (Department of Mineral Resources and Energy, 2020). The policy aims to enable the industry to grow and advance in participation in the mainstream economy and efficiently use its resources (DMRE, 2020). Specifically, it is designed to create an environment that not only allows the sector to contribute to the economic imperatives of job creation and poverty alleviation in South Africa but also purposefully encourages it to do so (Mutemeri and Petersen, 2002). Tensions between large-scale mining (LSM) and small-scale miners are often a result of the perceived threat to LSM through encroachment, illegal activities, and their relationship with local host communities (Maconachie and Hilson, 2011). Initiatives by the LSM to establish ties with host mining communities have been emerging; however, these relationships require patience and realistic expectations from all parties in addressing the needs of small-scale operators and their communities (World Bank, 2013). Very often, these relationships are marred with distrust and are also a result of poverty and lack of opportunities (Hilson, 2009). Opportunities for the ASM sector to do business with LSM present possibilities for establishing economic value chains in those communities (Buxton, 2013).

The challenges faced by ASM include environmental degradation due to limited access to specialised environmental and geological expertise resulting from financial constraints, occupational health and safety risks, lack of proper infrastructure and equipment, lack of funding, the rise of illegal miners, and conflicts over resource access, often characterised by power dynamics between genders (Hinton, Veiga, and Beinhoff, 2003). The inadequate regulation and monitoring of ASM can escalate social issues such as gender inequality, child labour, and discrimination against disabled people (ILO, 1999). We conclude that responsible ASM practices could be fostered through collaborative efforts with various stakeholders, including the government: such as the Department of Mineral Resources and Energy, community leaders, and the ASM community (Mutemeri, Sellick and Mtegha, 2010). These practices, when implemented effectively, can benefit local communities (Hilson, 2002). ASM has a complex and dynamic influence on social communities, shaping livelihoods, local economies, and social dynamics.

Through support and proper policy implementation and monitoring, responsible ASM practices can improve livelihoods, promote compliance, and enhance the creation of local economies. Additionally, it will contribute towards GDP and create secondary economies (World Bank, 2013).

Keywords: Artisanal and small-scale mining, ASM, environmental degradation, health and safety risks, economic empowerment, poverty alleviation, South Africa, large-scale mining, LSM, local communities, gender dynamics, policy implementation, sustainable practices, formalisation, economic value chains, marginalised groups, socio-economic impact.

INTRODUCTION

Artisanal and small-scale mining (ASM) is a crucial economic activity in many developing regions, providing employment and livelihoods to millions of people worldwide, particularly in rural areas where formal employment opportunities are scarce (World Bank, 2013). ASM holds significant potential for empowering marginalised groups, including women, youth, and people with disabilities, by offering opportunities for economic empowerment and poverty alleviation. In the often-challenging landscape of rural development, this potential for empowerment serves as a beacon of hope (Hentschel, Hruschka, & Priester, 2002).

Beyond its economic contributions, ASM profoundly impacts local communities by supporting small businesses and stimulating local economies. The revenue generated from formalised ASM activities often remains within the community, further reinforcing local economic growth. This local economic stimulation is a clear and tangible benefit of ASM that positively impacts community members. However, the sector faces significant challenges. Environmental degradation, health and safety risks, inadequate infrastructure, and social issues such as gender inequality and child labour are critical concerns that must be addressed to ensure ASM's sustainability and positive impact (Hinton *et al*., 2003). Moreover, ASM activities are often located near large-scale mining (LSM) operations, and both sectors frequently share local communities. However, the lack of coherence and collaboration between these two players remains a persistent challenge. Achieving harmonious relations between LSM and ASM could significantly enhance the economic impact on local areas, offering broader development opportunities.

BACKGROUND ON ARTISANAL AND SMALL-SCALE MINING

Historical Context

ASM has been practised for centuries, primarily as a subsistence activity providing basic livelihoods to rural communities. Traditionally, ASM was an informal sector characterised by low technology and labour-intensive processes, often carried out by individuals or small groups. Historically, these activities were largely focused on extracting gold, diamonds, and other precious minerals from easily accessible deposits, primarily for local markets or as a means of trade.

However, as global demand for minerals increased, ASM expanded in both scale and significance. By the late 20th century, it had evolved from a predominantly subsistence activity into a more commercially significant sector. This transition was driven by a combination of rising global mineral prices, increased economic pressures in rural areas, and the depletion of easily accessible mineral resources. As a result, ASM became an essential livelihood strategy for millions, particularly in regions with limited formal employment opportunities (Hilson, 2009).

In many African, Asian, and Latin American countries, ASM has emerged as a critical contributor to national and local economies. It provides employment and income for millions who lack viable economic alternatives, often in areas where large-scale mining (LSM) operations are absent or inaccessible. Despite its economic importance, ASM remains largely informal, with many miners operating outside regulatory frameworks. This informality presents challenges but also highlights the sector's resilience and adaptability in the face of changing economic conditions (Hilson & McQuilken, 2014).

ASM in the Global Economy

Currently ASM plays a substantial role in providing a considerable amount of the world's supply of diverse minerals, such as gold, diamonds, tin, and tantalum. It plays a significant role in the world economy by producing minerals that are essential for many high-demand sectors. ASM, as reported by the World Bank in 2013, accounts for almost 20% of the global gold supply and up to 80% of some gemstones. This significant contribution highlights the significance of ASM in the worldwide mineral economy, especially in areas like electronics, jewellery, and industrial production, where there is a great demand for these resources.

Although ASM holds economic importance, it is frequently disregarded in international conversations about mining and development. The talks are usually dominated by LSM operations, which result in a lack of awareness and support for ASM activities. The emphasis on LSM not only marginalises ASM but also overlooks the distinct challenges and prospects that the sector presents. The lack of attention to this issue has important consequences for the large number of individuals who rely on ASM for their incomes, since it frequently leads to inadequate legislation, insufficient funding, and a lack of initiatives to formalise and promote the sector (Hilson, 2009).

Furthermore, the lack of attention given to ASM in global discussions on mining hinders the acknowledgement of its potential role in promoting sustainable development. Although ASM has been linked to environmental and social difficulties, it also offers significant promise for reducing poverty, promoting economic empowerment, and fostering rural development. It is essential to adopt a comprehensive approach that incorporates ASM into worldwide mining and development frameworks in order to effectively utilise its potential and tackle the difficulties encountered by ASM communities.

ASM IN DIFFERENT REGIONS

ASM in Sub-Saharan Africa

ASM plays a crucial role in sustaining numerous rural communities in Sub-Saharan Africa. The mining industry is especially significant in countries like Ghana, Tanzania, and the Democratic Republic of Congo (DRC), where a substantial number of people are involved in the extraction of precious minerals such as gold and diamonds. ASM is of utmost importance in these regions, since it serves as a vital source of income, particularly in locations where formal job possibilities are scarce.

Nevertheless, ASM in Sub-Saharan Africa is frequently marked by informal and uncontrolled activities, posing substantial difficulties. The absence of formalisation in the sector has resulted in extensive environmental damage and numerous social tensions. In Ghana, the environmental consequences of ASM, namely the illicit mining activities referred to as 'galamsey' have had a significant and detrimental effect. Water systems and agricultural fields have seen substantial harm as a result (Aubynn, 2009). Furthermore, these illicit operations have played a role in the degradation of local ecosystems by causing deforestation, soil erosio, and pollution, so jeopardising their long-term survival.

Notwithstanding these difficulties, ASM continues to be a crucial means of livelihood for numerous rural families in Sub-Saharan Africa. The income gained from ASM activities allows several households to fulfil their essential requirements, invest in education, and enhance their standard of living. ASM has become a crucial component of the local economy in countries such as Tanzania and the DRC, playing a significant role in promoting rural development and attempts to reduce poverty. Nevertheless, the complete capacity of ASM to make a positive impact on sustainable development has not been achieved because of persistent problems related to lack of formalisation, environmental deterioration, and social disputes (Hilson & McQuilken, 2014).

In order to tackle these difficulties, there is an increasing acknowledgement of the necessity for the formalisation and improved control of ASM in Sub-Saharan Africa. It is crucial to make efforts to incorporate ASM into the formal economy, offer technical assistance, and encourage ecologically sustainable methods. This is necessary to maximise the sector's beneficial influence while minimising its negative effects.

ASM in South America

The ASM sector in South America is diverse, with activities spanning various countries and mineral resources. Key examples include gold mining in the Amazon Basin and emerald mining in Colombia. While ASM provides essential livelihoods for many rural communities across the continent, it also poses significant environmental and health challenges.

In the Amazon, ASM – particularly gold mining – has been a major driver of deforestation and mercury pollution. The use of mercury in gold extraction has led to severe environmental degradation, contaminating water bodies and ecosystems, and posing serious health risks to local communities. The widespread mercury pollution has had long-lasting effects, including bioaccumulation in fish, a critical food source for many indigenous and rural populations (Veiga *et al.*, 2006). The scale of deforestation associated with ASM in the Amazon also contributes to climate change by reducing the region's capacity to sequester carbon, further compounding global environmental challenges.

Despite these challenges, there are examples of successful formalisation and sustainability initiatives within the ASM sector in South America. In Colombia for instance, government programmes have been implemented to support small-scale miners in obtaining legal status and adopting more sustainable practices. These efforts have led to improved working conditions, reduced environmental impacts, and greater economic stability for ASM communities (Hilson & McQuilken, 2014). The formalisation process has involved training programmes, technical assistance, and the introduction of cleaner technologies, such as mercury-free gold processing methods. These initiatives have not only helped to mitigate the negative effects of ASM but also demonstrated the potential for sustainable mining practices in the region.

The experience in Colombia highlights the importance of government support and regulation in transforming ASM into a more sustainable and legally recognised sector. While challenges remain, particularly in regions with weak governance and high levels of informality, the successes in Colombia offer valuable lessons for other South American countries looking to improve the environmental and social outcomes of their ASM sectors.

ASM in Southeast Asia

The ASM industry in South America is characterised by its diversity, as it encompasses a wide range of operations across many countries and mineral resources. Notable instances include the extraction of gold in the Amazon Basin and the extraction of emeralds in Colombia. ASM is crucial for the economic sustenance of numerous rural people in Africa. However, it also presents substantial environmental and health risks.

Gold mining in the Amazon, namely ASM, has significantly contributed to deforestation and the contamination of mercury. The utilisation of mercury in the process of gold extraction has resulted in significant environmental deterioration, polluting aquatic systems and ecosystems, and presenting substantial health hazards to nearby residents. The extensive contamination of mercury has resulted in enduring consequences, such as the buildup of this toxic substance in fish. This poses a significant threat to the food supply of numerous indigenous and rural communities (Veiga *et al.,* 2006). The extent of deforestation linked to ASM in the Amazon region also exacerbates climate change by diminishing the area's ability to absorb carbon, hence intensifying worldwide environmental issues.

Notwithstanding these difficulties, there are instances of prosperous efforts to establish formal structures and ensure long-term viability in the ASM industry in South America. In Colombia, the government has created programmes to assist small-scale miners in acquiring legal status and adopting environmentally sustainable techniques. The endeavours have resulted in enhanced labour conditions, diminished ecological footprints, and increased financial stability for ASM populations (Hilson & McQuilken, 2014). The formalisation process has encompassed training programmes, provision of technical help, and the implementation of greener technologies, such as mercury-free gold processing methods. These measures have not only alleviated the adverse impacts of ASM but also showcased the possibility of implementing sustainable mining methods in the region.

The case of Colombia underscores the significance of governmental assistance and oversight in converting ASM into a more environmentally sound and officially acknowledged industry. Although there are still obstacles to overcome, especially in areas with inadequate governance and significant levels of informality, Colombia's achievements provide important insights for other South American nations seeking to enhance the environmental and social results of their ASM industries.

CHALLENGES IN FORMALISING ASM

Legal and Regulatory Barriers

A key obstacle in formalising ASM is dealing with the intricate and frequently constraining legal systems that regulate mining operations. The acquisition of mining licences in numerous nations is arduous, costly, and riddled with bureaucratic obstacles. The intricate nature of the situation poses challenges for small-scale miners to adhere to legal obligations, resulting in a significant number of businesses being forced into the informal and criminal sectors (Hilson & Potter, 2003).

The regulatory framework for ASM is often characterised by a dearth of unambiguous, consistent regulations and insufficient enforcement measures. Many governments have mining regulations that are primarily tailored for large-scale operations and do not adequately address the specific requirements and circumstances of ASM. Consequently, the legal system may not offer sufficient assistance or motivations for small-scale miners to legalise their operations. This can result in a pervasive lack of formality, as miners engage in activities without proper licences or permissions, thereby undermining efforts to efficiently regulate the sector (World Bank, 2013).

Moreover, the exorbitant expenses linked to acquiring and the upkeep of mining permits encompassing charges, levies, and conformity expenditures, can pose a significant obstacle for small-scale miners. Due to this financial obstacle, miners frequently choose to work outside the official system, which exposes them to fewer laws but also deprives them of legal safeguards and support services. ASM operators face a greater financial burden due to their restricted access to credit and financial services, which reinforces their status in the informal economy.

The absence of explicit legislation further exacerbates disputes around land utilisation and resource entitlements. ASM operations often intersect with other land uses, such as agriculture or protected areas, resulting in conflicts and occasionally violent confrontations. To achieve effective formalisation, it is necessary to deal with these issues by implementing transparent and inclusive systems for land management and resource allocation.

In order to surmount these legal and regulatory obstacles, it is imperative to implement customised regulations that acknowledge the unique attributes of ASM. Streamlining the licencing procedure, cutting down expenses, and offering technical and financial assistance can aid in expediting the formalisation of ASM. Furthermore, it is essential to establish precise laws and enhance the procedures for enforcing them in order to ensure that ASM operates within legal frameworks and minimises adverse environmental and social effects.

Financial Constraints

The presence of financial obstacles poses a substantial hurdle to the process of formalising ASM. Small-scale miners often encounter challenges in obtaining credit and financial services, which are crucial for acquiring equipment, enhancing mining operations, and complying with regulatory obligations

(Hentschel *et al*., 2002). The absence of adequate financial assistance impedes their capacity to invest in more effective and sustainable methods, hence perpetuating patterns of limited output, survival-based living, and destitution.

A significant number of ASM operations are marked by antiquated or basic machinery, resulting in restricted efficiency and heightened ecological consequences of mining operations. Miners face challenges in enhancing their operations due to the lack of contemporary technology and insufficient funding for equipment modifications. As a result, they experience inefficient extraction procedures and poor economic returns. The financial restriction not only hampers operational efficiency but also worsens the environmental deterioration linked to ASM. This is because miners are frequently compelled to employ dangerous procedures, such as mercury amalgamation, for extracting gold.

In addition, the absence of access to official financial services restricts ASM operators' choices when it comes to acquiring operating cash or obtaining loans. Conventional financial institutions may perceive ASM as a sector with a high level of risk. Consequently, they may exhibit hesitancy in extending loans or credit to small-scale miners. This hesitancy is intensified by the casual nature of numerous ASM operations, which can additionally restrict their ability to get financial resources and services.

The lack of financial assistance also hampers the ability of ASM operators to adhere to regulatory mandates. Complying with legal requirements often incurs expenses associated with acquiring licences, establishing environmental management protocols, and enhancing safety conditions. Due to insufficient financial resources, a significant number of miners are unable to fulfil these standards, leading to their persistence in the informal sector.

In order to overcome these financial limitations, it is crucial to create inventive financial strategies and assistance programmes that are specifically designed to meet the requirements of ASM operators. This may involve offering microloans, grants, or alternative financial aid to assist miners in obtaining essential equipment and technology. In addition, the development of financial products and services tailored to the ASM sector can facilitate the connection between miners and established financial institutions. Enhancing the understanding of financial concepts and providing education on financial management will allow ASM operators to make more informed financial choices and allocate their resources more efficiently.

Social and Cultural Barriers

The formalisation of ASM is greatly affected by social and cultural variables. ASM is intricately intertwined with local traditions and cultural practices in numerous places, which adds complexity and sensitivity to the process of integrating formalisation initiatives (Hilson & McQuilken, 2014). The subsequent social and cultural obstacles are especially relevant.

Cultural Traditions and Practices: In several regions, ASM is not solely a commercial endeavour, but also a customary practice deeply rooted in culture. The deeply rooted nature of this status quo might provide challenges when attempting to implement official regulations or modifications that could potentially disturb long-standing customs and practices. The resistance to formalisation may arise from the belief that it poses a danger to local customs and community institutions. Therefore, any attempts to establish formal systems for ASM should take into account the cultural settings and include traditional activities in the legislative frameworks, where feasible.

Gender dynamics frequently impact the allocation of advantages among ASM communities. Women engaged in ASM, whether directly or indirectly, often have substantial obstacles in obtaining resources, participating in decision-making, and receiving financial advantages. Women's involvement in formalised ASM activities and their access to the sector's economic potential might be constrained by social norms and gender roles, leading to inequitable benefits (Hinton *et al*., 2003). It is essential to prioritise gender inclusion in formalisation initiatives in order to attain outcomes that are more fair and enduring.

Social hierarchies and inequality can also impact the process of formalising ASM due to existing power systems. Local leaders or powerful persons in numerous areas often exert substantial authority over ASM operations and resources. This can result in an inequitable allocation of advantages, as marginalised groups are frequently excluded from the decision-making procedures and economic rewards. To ensure that all community members benefit from the formalisation of ASM, it is crucial to address social hierarchies and promote inclusive governance structures.

Community Resistance: Local populations may resist formalisation attempts because of apprehensions related to relinquishing authority over traditional mining regions or anxieties about heightened monitoring and regulation. By utilising participatory methods, such as involving miners and local stakeholders in the development and execution of formalisation policies, it is possible to effectively address these concerns and establish confidence.

THE ROLE OF TECHNOLOGY AND INNOVATION IN ASM

Enhancing Productivity and Efficiency

Technology and innovation are essential for enhancing the productivity and efficiency of ASM operations. Utilising contemporary mining equipment and methodologies can result in substantial advantages, such as heightened production, diminished ecological consequences, and enhanced labour conditions.

Contemporary Mining Equipment: The implementation of state-of-the-art mining equipment, such as enhanced panning tools, hydraulic systems, and mechanised excavation tools, can optimise the effectiveness of ASM operations. These technologies facilitate the processing of bigger quantities of material at a faster rate and with enhanced accuracy, resulting in increased productivity for miners. For instance, employing effective rock crushers and grinders can enhance the quantity of ore handled and diminish the need for physical labour.

A significant advancement in ASM is the creation and endorsement of gold extraction techniques that do not include the use of mercury. Conventional gold mining frequently employs mercury, which presents significant health hazards to miners and pollutes the environment. Contemporary methods, such as gravity concentration, flotation, and cyanide leaching (when handled responsibly), provide safer and more ecologically sound options. By implementing these strategies, the level of mercury contamination can be greatly reduced, leading to enhanced safety and sustainability of ASM operations (Hilson, 2009).

Technology can also help reduce the environmental impact of ASM. Advancements in waste management, water treatment, and reclamation methods aid in reducing the negative impacts of mining operations. For example, the advancement of more efficient tailings management systems can decrease the likelihood of environmental pollution and enhance the extraction of precious minerals from discarded materials (Veiga *et al.*, 2006).

Improved Safety: Technological developments can enhance the safety of ASM operations. Implementing enhanced ventilation systems, protective clothing, and real-time monitoring technology can effectively mitigate the hazards linked to underground mining, including the exposure to noxious gases and unstable ground conditions. Implementing safety advancements not only safeguards miners but also enhances the stability and efficiency of operations.

Teaching and Capacity Building: Technology can enhance the process of teaching and developing the skills and abilities of ASM operators. Miners can utilise digital tools, such as mobile applications and internet platforms, to gain access to information, training resources, and technical help. These tools can enhance the proficiency of miners, advocate for optimal methods, and facilitate the implementation of innovative technology.

In order to effectively harness the advantages of technology and innovation in ASM, it is imperative to overcome obstacles that hinder its implementation. This encompasses facilitating the availability of cost-effective and suitable technology, delivering instruction and support, and promoting collaborations among various parties, such as governmental bodies, technology suppliers, and mining communities. Through the strategic utilisation of technology and innovation, ASM has the potential to enhance productivity and efficiency, while simultaneously minimising its environmental impact and enhancing the well-being of miners.

Promoting Sustainability
Advanced technologies are crucial in supporting the sustainability of ASM activities. By using environmentally friendly and resource-efficient technology, ASM can reduce its negative impact on the environment, improve operational efficiency, and support long-term sustainable development. Technology plays a crucial role in promoting sustainability in ASM in various important areas, such as: Utilising solar-powered equipment is a notable progress for ASM operations, especially in distant and off-grid locations. Solar energy has the capability to operate a wide range of mining tools and equipment, hence decreasing dependence on diesel or other fossil fuels. This move not only decreases the amount of greenhouse gases released into the atmosphere but also decreases the expenses associated with running mining operations. Solar technology can enhance mining operations and promote sustainable practices through the use of solar-powered illumination and water pumps (Siegel & Veiga, 2009).

Water recycling systems play a vital role in mitigating the environmental consequences of ASM, especially in areas with limited water resources. Deploying water reclamation systems in mining operations can significantly reduce water usage and mitigate the risk of polluting nearby water sources. Implementing efficient water management strategies is crucial for mitigating problems like sedimentation, pollution, and water resource depletion, hence promoting environmental sustainability. Substitutes for Mercury: Innovations in the extraction of gold, such as gravity concentration, flotation, and other chemical processes, provide environmentally sustainable alternatives to the use of mercury. These approaches have the potential to greatly diminish mercury pollution, which is a serious issue in conventional gold mining practices. By implementing mercury-free technologies, ASM can reduce health hazards for miners and alleviate environmental pollution, hence fostering a more hygienic and secure mining environment (Siegel & Veiga, 2009).

Mobile technology enhances communication, coordination, and market accessibility for ASM operators. Mobile devices and software can establish connections between miners, buyers, suppliers, and financial institutions, improving market efficiency and promoting financial inclusion. Mobile platforms, for instance, have the capability to offer up-to-date data on mineral prices, facilitate electronic transactions, and facilitate access to financial services like micro-loans and insurance. This connectivity enables the integration of ASM operators into formal markets and financial systems, hence improving economic sustainability (World Bank, 2013).

Data-driven management uses data-driven technology like geographic information systems and remote sensing to enhance the management and planning of ASM activities. These technologies provide more accurate resource mapping, enhanced environmental monitoring, and improved risk assessment. Through data utilisation, miners may make well-informed decisions, optimise resource utilisation, and apply efficient methods for environmental management.

Challenges to Technology Adoption
While innovative technologies offer significant potential to enhance the productivity, efficiency, and sustainability of ASM, their adoption is not without challenges. These barriers can impede the widespread implementation of new technologies and limit their benefits. Key challenges include: High Costs: The initial investment required for adopting new technologies can be a significant barrier for ASM operators, who often operate with limited financial resources. Modern mining equipment, solar-powered systems, and advanced processing technologies can involve significant upfront costs, which may be prohibitive for small-scale miners. Without access to affordable financing options or

subsidies, many miners may find it difficult to afford and implement these technologies (Hilson & McQuilken, 2014).

Lack of Technical Expertise: The successful implementation and operation of new technologies often require specialised technical knowledge and skills. Many ASM operators may lack the expertise to operate and maintain advanced equipment or implement new processes effectively. This skills gap can hinder the adoption of innovative technologies and reduce their potential impact. Training and capacity-building programmes are essential to equip miners with the skills to use and benefit from new technologies (Hilson & McQuilken, 2014).

Limited Market Access: Access to markets for new technologies can be restricted, particularly in remote or underserved areas. Technology providers may be unwilling or unable to reach small-scale mining communities due to logistical challenges, high distribution costs, or limited market demand. Additionally, the lack of established supply chains for spare parts and maintenance services can complicate technology adoption and upkeep (Hilson & McQuilken, 2014).

Cultural Resistance: Cultural resistance to change can also pose a significant challenge to the adoption of new technologies. There may be scepticism or reluctance to adopt new methods in communities where traditional mining practices are deeply ingrained. This resistance can stem from a strong attachment to traditional ways of working, distrust of new technologies, or concerns about the impact of change on local customs and practices (Hinton *et al.*, 2003). Engaging with local communities and demonstrating the benefits of new technologies through participatory approaches can help overcome these barriers.

Inadequate Infrastructure: In many ASM regions, inadequate infrastructure, such as unreliable power supply, poor transportation networks, and limited access to communication technologies, can hinder the implementation of advanced technologies. Developing the necessary infrastructure to support technology adoption is crucial for ensuring that ASM operators can effectively use and maintain new tools and systems.

POLICY RECOMMENDATIONS AND FUTURE DIRECTIONS

Strengthening Regulatory Frameworks

Governments must strengthen regulatory frameworks to enhance the formalisation and sustainability of ASM. Effective regulation can facilitate legal operation, promote environmental and social standards, and ensure the sector's long-term viability. Critical recommendations for improving regulatory frameworks include:

Streamlining Licencing Processes: Simplifying and expediting the licencing process is crucial for encouraging small-scale miners to transition from informal to formal operations. Governments should establish clear, accessible procedures for obtaining mining permits and licences, reducing bureaucratic hurdles and associated costs. Providing a simplified, tiered licencing system that accommodates different scales of mining operations can make it easier for ASM operators to comply with legal requirements (World Bank, 2013).

Providing Financial Incentives: Financial incentives can help alleviate the economic burden of formalising ASM activities. Governments can offer subsidies, grants, or low-interest loans to support acquiring modern equipment, adopting sustainable practices, and compliance with regulatory standards. Financial support can also include tax breaks or reduced fees for licences and permits, making it more affordable for small-scale miners to operate legally (World Bank, 2013).

Ensuring Fair and Transparent Regulations: Developing fair and transparent regulations is essential for building trust and encouraging compliance within the ASM sector. Regulations should be developed in consultation with ASM communities and stakeholders to ensure they address the sector's specific needs and challenges. Transparent regulatory processes and clear communication can help prevent corruption and ensure that regulations are implemented effectively and equitably (Hilson & Potter, 2003).

Improving Enforcement Mechanisms: Effective enforcement is crucial for combating illegal mining and ensuring environmental and safety standards adherence. Governments should strengthen monitoring and enforcement mechanisms to address illegal activities and promote compliance with regulations. This includes investing in training and resources for regulatory agencies, utilising technology for real-time monitoring, and establishing mechanisms for reporting and addressing violations (Hilson & Potter, 2003).

Promoting Environmental and Safety Standards: Integrating environmental and safety standards into regulatory frameworks helps minimise the negative impacts of ASM. Governments should establish clear guidelines for environmental management, waste disposal, worker safety and provide support for miners to meet these standards. Encouraging the adoption of best practices through training and technical assistance can help improve operational sustainability and reduce environmental degradation (World Bank, 2013).

Fostering Multi-Stakeholder Collaboration: Collaboration between governments, mining communities, industry stakeholders, and NGOs is crucial for developing and implementing effective regulatory frameworks. Multi-stakeholder dialogue can help identify challenges, share best practices, and coordinate efforts to support ASM formalisation and sustainability. Engaging with all relevant parties ensures that regulatory policies are well-informed and effectively address the sector's needs.

Enhancing Access to Finance

Access to finance is crucial for developing and sustaining the ASM sector. Improved financial access can enable small-scale miners to invest in modern equipment, adopt sustainable practices, and transition from informal to formal operations. To enhance access to finance for ASM, the following strategies are recommended:

Developing Tailored Financial Products: Financial institutions should create products specifically designed to meet the needs of small-scale miners. This includes offering microloans with flexible terms and conditions that accommodate the unique financial circumstances of ASM operators. Additionally, developing grant programmes to support initial investments in equipment and technology can help reduce the financial barriers to formalisation. Insurance products tailored to ASM operations can also protect miners from financial losses due to accidents, environmental damage, or market fluctuations (Hentschel *et al.*, 2002).

Expanding Financial Inclusion: Increasing financial inclusion for ASM operators is essential for fostering sector development. This involves improving access to banking services, such as savings accounts, credit facilities, and digital payment systems. Mobile banking and digital financial services can effectively reach remote mining communities and provide secure, accessible financial options. By expanding financial services and promoting financial literacy, miners can better manage their finances and access the resources needed for operational improvements.

Supporting Financial Literacy and Training: Providing financial literacy and education is crucial for helping ASM operators make informed financial decisions. Financial literacy programmes can cover topics such as budgeting, saving, accessing credit, and managing investments. Training programmes should be designed to address the specific needs and challenges faced by ASM operators, enabling them to effectively use financial products and services to improve their operations and sustainability.

Facilitating Partnerships with Development Organisations: Collaborations with international development organisations can provide ASM additional financial and technical support. These partnerships can help mobilise resources, such as grants, technical assistance, and capacity-building programmes. Development organisations can also offer expertise in designing and implementing financial solutions tailored to the ASM sector and supporting initiatives that promote formalisation and sustainability (Hentschel *et al.*, 2002).

Creating Risk Mitigation Mechanisms: Financial institutions and governments should develop mechanisms to mitigate the risks associated with lending to ASM operators. This can include providing risk guarantees, creating credit risk-sharing arrangements, or establishing dedicated funds to support ASM projects. Risk mitigation strategies can help build confidence among lenders and investors, making it easier for small-scale miners to access the financing they need for growth and improvement.
Promoting Innovative Financing Models: Exploring innovative financing models, such as community-based savings groups, impact investing, and blended finance approaches, can provide alternative funding sources for ASM. These models can leverage collective resources, align investor interests with social and environmental outcomes, and provide flexible financing options that cater to the needs of small-scale miners.

Promoting Gender Equality and Social Inclusion
Advocating for gender equality and social inclusion is crucial to cultivating a fairer and more sustainable ASM industry. Promoting gender equality and inclusivity in ASM can result in better social results and increased efficiency in mining operations. To promote gender equality and social inclusion in ASM, it is advised to implement the following strategies:
Guaranteeing Equitable Access to Resources and Opportunities: Policies and initiatives should be formulated to ensure that women and marginalised communities have equitable access to mining resources, training, and support services. This encompasses offering specific financial aid, specialised instruction, and the opportunity to utilise state-of-the-art equipment. To make the sector more inclusive and supportive of different participants, it is essential to address the specific requirements and challenges these groups face, such as restricted access to financing or training opportunities (Hinton *et al.*, 2003).

Facilitating the practice of inclusive decision-making: Ensuring the participation of women and marginalised groups in decision-making processes at every stage of ASM operations can result in more comprehensive and efficient outcomes. This encompasses involvement in community meetings, advisory boards, and policy formulation. Including these groups in the decision-making process regarding mining methods, resource management, and community development can effectively address their needs and objectives, resulting in fairer and more environmentally-friendly outcomes (Hilson & McQuilken, 2014).

Overcoming Social and Cultural Obstacles: Social and cultural obstacles can impede the involvement of women and marginalised groups in ASM. In order to surmount these obstacles, it is crucial to actively involve oneself with the local community and strive to transform discriminatory practices and attitudes. This may entail executing awareness-raising efforts, advocating for positive role models, and establishing supportive environments that question conventional gender roles and social conventions. It is imperative to make concerted efforts to safeguard women and marginalised groups against exploitation and violence in the mining sector (Hilson & McQuilken, 2014).

Offering Tailored Assistance and Instruction: Creating and executing training initiatives designed for women and marginalised communities can enhance their abilities and self-assurance in artisanal and small-scale mining endeavours. The training programme should encompass instruction in technical skills, safety protocols, financial administration, and cultivating leadership abilities. By providing these groups with essential information and abilities, they may make a more valuable contribution to and derive more significant benefits from ASM operations.

Promoting and facilitating women's leadership and entrepreneurship in ASM can enhance gender equality and economic empowerment. This includes offering guidance, facilitating connections, and granting access to resources for business growth. Assisting mining firms and efforts run by women can contribute to dismantling obstacles and establishing exemplary figures for future generations (Hinton *et al.*, 2003).

Enacting Gender-Sensitive Policies and Programmes: Governments and organisations should create and enforce policies and programmes sensitive to gender and tackle the distinct obstacles encountered by women and marginalised groups in ASM. These policies should incorporate rules for ensuring equal access to resources, implementing safety measures, and providing support services, with a specific focus on promoting gender equality. It is crucial to monitor and evaluate the effects of these programmes to ensure that they effectively advance gender equality and social inclusion.

By prioritising gender equality and social inclusion, the ASM sector has the potential to become more fair and enduring, as it may benefit from the many viewpoints and contributions of all participants. These endeavours will result in enhanced social results and increased efficiency of mining operations.

Encouraging Innovation and Technology Adoption
Encouraging the use of cutting-edge technologies in the ASM industry is essential for improving production, sustainability, and overall operational efficiency. Governments and development organisations can significantly influence the progress of technology by developing strategies that promote the use of technology and solve any obstacles that may arise. Some crucial suggestions are:
Offering Technical Training: Technical training is crucial for equipping ASM operators with the necessary expertise to proficiently use new technologies. Governments and development organisations should provide training programmes that specifically target contemporary mining practices, equipment operation, and maintenance. The training should be pragmatic and customised to the unique requirements of ASM communities, guaranteeing that miners can proficiently execute and gain advantages from technological advancements (Veiga *et al*., 2006).

Providing Monetary Incentives: Monetary incentives can help mitigate the expenses linked to the adoption of novel technology. These incentives may comprise grants, subsidies, or low-interest loans to facilitate the acquisition of contemporary equipment, adoption of sustainable practices, and research and development endeavours. Offering financial assistance can facilitate the ability of small-scale miners to invest in and incorporate cutting-edge technology that enhances their operations (Veiga *et al*., 2006).

Promoting Research and Development: Allocating resources towards research and development is essential for the progress of technology aimed at tackling the specific obstacles encountered by ASM. Government entities and development organisations should allocate funds towards research and development endeavours that specifically target creating innovative tools, processes, and solutions well-suited to small-scale mining operations. Engaging in partnerships with academic institutions, industry specialists, and technology providers can facilitate the advancement of new ideas and the development of realistic, adaptable solutions for the ASM sector (Veiga *et al*., 2006).

Promoting the Advantages of Technological Benefits: It is crucial to raise awareness regarding the advantages of contemporary technologies in order to foster their adoption. Awareness campaigns can promote the benefits of cutting-edge solutions, like increased productivity, minimised environmental footprint, and heightened worker safety. Presenting effective case studies and highlighting the favourable results of technology implementation can enhance ASM operators' confidence and encourage them to adopt new techniques (Hilson, 2009).

Addressing cultural barriers is crucial in overcoming opposition to change and facilitating the use of technology. To surmount these obstacles, it is crucial to actively include and collaborate with the local people in the process of adopting technology. This encompasses comprehending indigenous customs and rituals, attending to apprehensions, and showcasing how novel technologies might supplement or elevate preexisting approaches. Adopting collaborative methods that uphold cultural values and practices can aid in facilitating more seamless transitions to modern technologies (Hilson, 2009).

Enhancing Accessibility to Technology and Support Services: Enhancing the availability of technology and support services is crucial for successful implementation. This encompasses establishing local technology hubs, providing access to technical support and maintenance services, and creating networks for knowledge sharing and collaboration among ASM operators. Providing miners with adequate resources and support is crucial for enabling them to adopt and utilise new technologies efficiently.

Governments and development organisations may assist the ASM industry in attaining higher productivity, sustainability, and overall success by promoting innovation and the adoption of technology through these approaches. By providing support for technological developments, small-scale miners can optimise their operations, mitigate environmental impacts, and improve their lives.

CONCLUSION

ASM is a diverse and intricate industry that significantly impacts the livelihoods and economic prospects of millions of people worldwide. Although ASM is economically important, it also poses significant issues that need to be tackled to guarantee its sustainable existence and beneficial effects on communities and the environment.

ASM plays a substantial role in the worldwide provision of minerals, such as gold and gemstones, and acts as a vital source of income for individuals residing in rural and economically marginalised regions. Nevertheless, the industry encounters obstacles such as ecological deterioration, potential threats to health and safety, legal and regulatory impediments, and financial limitations. It is crucial to tackle these difficulties to enhance the sector's sustainability and promote fair distribution of its benefits (World Bank, 2013).

Proposed policy suggestions: To facilitate the formalisation and advancement of ASM, various crucial measures can be employed:
Enhancing Regulatory Frameworks: Streamlining licencing procedures, offering financial incentives, guaranteeing equitable and transparent laws, and enhancing enforcement mechanisms can facilitate the formalisation of ASM activities and encourage compliance with environmental and safety norms.
To improve access to finance and support the growth of ASM, it is essential to develop customised financial products, increase financial inclusion, promote financial literacy and training, foster partnerships with development organisations, and establish risk mitigation mechanisms.

Advancing Gender Equality and Social Inclusion: Guaranteeing equitable access to resources, fostering inclusive decision-making, tackling social and cultural obstacles, offering specialised support and training, and enforcing policies that consider gender can improve social fairness in ASM communities.
Promoting innovation and the adoption of technology can be achieved through various means, such as providing specialised training, offering financial incentives, supporting research and development efforts, increasing awareness of the benefits of technology, addressing cultural obstacles, and facilitating access to technology and support services. These measures can effectively drive innovation and enhance operational efficiency.

Future Directions: Ongoing endeavours are necessary to tackle the obstacles confronting ASM and to use its potential for beneficial influence. Effective solutions require the collaboration of governments, development organisations, financial institutions, and local people. Governments should prioritise regulatory reform, financial access, social inclusion, and technical innovation to promote a more sustainable and fairer ASM sector that benefits miners and their communities while reducing adverse environmental and social effects.

To summarise, although ASM offers both advantages and difficulties, implementing strategic measures and enacting supporting policies can facilitate realising its complete potential. This, in turn, will enhance the outcomes for miners and contribute to the sustainable development of the regions where ASM is active.

REFERENCES

Aubynn, A. (2009). Sustainable solution or a marriage of inconvenience? The cohabitation of large-scale mining and artisanal and small-scale mining on the Abosso Goldfields concession in Western Ghana. Resources Policy, 34(1-2), pp. 64-70.

Hentschel, T., Hruschka, F. and Priester, M. (2002) Global Report on Artisanal & Small-Scale Mining. Report commissioned by the Mining, Minerals and Sustainable Development (MMSD) project of the International Institute for Environment and Development (IIED). London: IIED.

Hilson, G. (2009). Small-scale mining, poverty and economic development in sub-Saharan Africa: An overview. Resources Policy, 34(1-2), pp. 1-5.

Hilson, G. and McQuilken, J. (2014). Four decades of support for artisanal and small-scale mining in sub-Saharan Africa: A critical review. The Extractive Industries and Society, 1(1), pp. 104-118.

Hilson, G. and Potter, C. (2003). Why is illegal gold mining activity so ubiquitous in rural Ghana? African Development Review, 15(2-3), pp. 237-270.

Hinton, J.J., Veiga, M.M. and Beinhoff, C. (2003). Women and artisanal mining: Gender roles and the road ahead. In: Hilson, G., ed. The Socio-Economic Impacts of Artisanal and Small-Scale Mining in Developing Countries. Lisse: Swets Publishers, pp. 149-188.

Siegel, S. and Veiga, M.M. (2009). Artisanal and small-scale mining as an extra-legal economy: De Soto and the redefinition of "formalization". Resources Policy, 34(1-2), pp. 51-56.

Veiga, M.M., Maxson, P.A. and Hylander, L.D. (2006). Origin and consumption of mercury in small-scale gold mining. Journal of Cleaner Production, 14(3-4), pp. 436-447.

World Bank (2013) Artisanal and Small-Scale Mining. Washington, D.C.: World Bank.

Environmental, Social and Governance considerations and sustainable development goals contributions in the minerals industry: A complementary perspective

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Mining companies worldwide are increasingly required to account for and disclose their impacts on society, environment and corporate governance through various reporting standards and frameworks. The perception of the contribution of the mining industry by various stakeholders is influenced by the extent to which it addresses the environmental, social and governance (ESG) issues in host communities. In November 2015, the United Nations adopted the 17 Sustainable Development Goals (SDGs) that cut across the economic, environmental, social, economic and governance factors. The recent years have seen the ESG issues gain prominence across the world. For investment and governance related reasons, business organisations are increasingly expected to publicly disclose the negative and positive impact of their activities and practices on the society, environment, economy and people. Indeed, this is a noble step in ensuring responsible and sustainable business practices in the settings in which private sector organisations operate. The irony is that the ESG discourse has lacked impactful integration with SDGs in the sustainability performance standards, frameworks and reports of corporate organisations.

The two acronyms ESGs and SDGs have been treated as dichotomies; as if they do not relate to each other or complement each other, while they seek to address the same objectives of responsible investment, good corporate citizenship and shared value creation. The SDGs are however a much broader framework, albeit non-mandatory, that can enhance responsible investment decision-making and shared value creation objectives than the three-pronged ESG framework considerations. Although non-mandatory, the SDG framework provides a useful starting point for an exercise towards achieving shared value outcomes in host communities. Linking ESG considerations to the SDGs provides business organisations with a comprehensive framework with which to measure the financial and non-financial impacts of their business activities on the wellbeing of society, environment, economy and people.

Drawing from a content analysis of published integrated annual reports of listed mining companies, this paper argues that the ESG impacts and contributions of mining firms need not be viewed as standalone activities but as interconnected and complementary. The paper argues that while the content analysis of the integrated annual reports and publicly available data sets depict an encouraging performance impact of mining companies on the SDGs, there is a need to review, consolidate and align the various fragmented reporting standards and frameworks on sustainability performance reports. It is important to link and integrate the ESG framework to the SDGs from financial and non-financial perspectives. This will in turn enhance the investment decision-making processes and accelerate shared value creation in a much more impactful, responsible and sustainable manner.

INTRODUCTION

In November 2015, the United Nations adopted the 17 Sustainable Development Goals (SDGs) that cut across the, environmental, social, governance (ESG) and economic factors (United Nations 2015, Columbia Centre for Sustainable Investments, United Nation and World Economic Forum). The recent years have seen the ESG issues gain prominence across the world. For investment and governance related reasons, business organisations are increasingly expected to publicly disclose the negative and positive impact of their activities and practices on the society, environment, economy and people (Fink 2022, Kenan Institute 2022, Schwab 2016). Indeed, this is a noble step in ensuring responsible and sustainable business practices in the settings in which private sector organisations operate. The irony is that the ESG discourse has been neglected or lacks impactful integration of SDGs in the sustainability performance standards, frameworks and reports of corporate organisations.

These two acronyms ESGs and SDGs have been treated as dichotomies as if they do not relate to each other or complement each other while in fact they seek to address the same objectives of responsible investment, good corporate citizenship and shared value creation. The SDGs are however a much broader framework that can better enhance responsible investment decision-making and shared value creation objectives than the three-pronged ESG framework considerations. The ESG narrative has gained more prominence than the SDG discourse. It is not surprising why this is so. More often than not the reference to debates and discussions on the ESGs take place as if the SDGs are non-existent. This partly emanates from the fragmented nature in which ESGs and SDGs are being addressed in the sustainability reports of listed companies. The mandatory reporting standards and frameworks with which the listed companies need to comply have not explicitly acknowledged and integrated the SDGs. It is assumed that those reporting standards and frameworks by default address matters relating to the SDGs. There is no clear demonstration of the integration of the SDGs in the reporting standards. The silence on the SDGs is deafening as if the ESG considerations are completely different from the SDGs, while in fact they are synonymous.

Why ESGs and SDGs Matter

There are numerous examples in South Africa where socio-economic development projects and programmes have stalled or failed to live up to expectations because of a lack of collaboration and partnership between stakeholders. Globally, business organisations are increasingly realising the value of gaining social acceptance in the communities in which they operate. I would like to argue that, at the level of implementation, the SDGs are more than the sum of it. They are not merely about compliance but about what is good for society, environment and people, is good for business as well. The objective of each of the SDGs reveals that the goals are a good vehicle for corporate organisations to responsibly create social and business shared values in the settings in which they operate. Indeed, business cannot singlehandedly achieve all the SDG goals without the support of other stakeholders. This is what the objectives of SDG 17 seek to achieve – collaboration and partnership – a point I will return to later in this paper.

In December 2019, the founder and chairman of the World Economic Forum, Klaus Schwab (2016), posed a poignant question to business and government leaders who were to gather in Davos in the following month of January 2020: *What kind of capitalism do we want?* A question that contemporary corporate leaders worldwide need to ponder and respond to. As he posed this question, Schwab was advocating for and challenging corporate leaders and investors at Davos to build what he called a better kind of capitalism that will sustain the social, environmental and economic needs of future generations. According to Schwab, this form of capitalism is stakeholder capitalism, which as he argues further, “positions private corporations as trustees of society and is clearly the best response to today’s social and environmental challenges.” To highlight the significance of stakeholder capitalism in tackling contemporary social, environmental and economic challenges, Schwab contrasts it to other types of capitalism, namely, shareholder capitalism and state capitalism. Stakeholder capitalism is centred on the principles of shared value creation. Harvard Business School Professor Michael Porter defined shared value as “corporate policies and practices that enhance competitiveness of a company while simultaneously advancing social and economic conditions in the communities in which it operates.”

In January 2022, in his annual letter to chief executive officers, Blackrock's CEO Laurence [Larry] Fink debunked the assertion that stakeholder capitalism was not good for business. Instead, he argues and agrees with Schwab that today's business environment requires corporates to serve the diverse interests of other stakeholders beyond the shareholders, if they are to be prosperous and profitable in the fiercely competitive global economy (Fink 2022). Stakeholder capitalism is at the core of shared value creation which the SDGs seek to achieve in building a sustainable planet for all. It is no longer a viable strategy for private sector organisations to serve only the interests of shareholders – what Schwab (2016) refers to as shareholder capitalism – whose modus operandi has been exclusively to promote the interests of private sector shareholders to the neglect of the needs of communities.

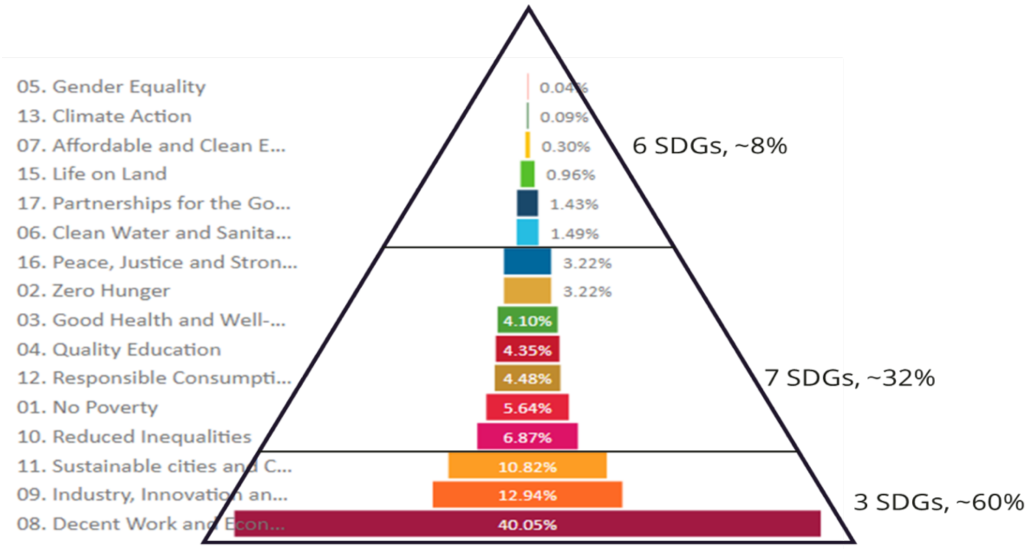
For a long a time until the 1970s, mixing business interests and societal interests was viewed as meddling with free-market principles, Schwab (2016). From the 1970s, the global economy saw the state directly participating in the business affairs of the private sector to champion the societal development interests. This was called state capitalism and was much more prominent in East-Asian economies. However, the shortcomings of state capitalism, Schwab argues, is not a sustainable viable model of capitalism as it is prone to corruption from within – an assertion that is not far-fetched in South Africa, as illustrated by the State Capture Commission reports. From the 1980s onwards the prominence of stakeholder capitalism proved suicidal for businesses that neglected the interests and needs of the communities in which they operated. It is within the realm of stakeholder capitalism (Schwab 2016; Kenan Institute 2022) that responsible investment decision-making and shared value creation objectives of ESGs and SDGs ought to be contextualised and understood. Nowadays, as has been highlighted by community unrest and labour strikes in South Africa, private sector organisations neglect the interests and needs of host communities at their peril.

Mainstreaming SDGs in their business activities is one of the means by which private sector companies can realise a return on their investment, create shared valued and be socially accepted in host communities. The SDGs present an ideal opportunity for corporate organisations to make a much more lasting impact in the communities in which they operate in a socially, economically, environmentally, technologically and humanly responsible manner.

The ESG and SDG Complementary Impacts in the Minerals Industry

Mining companies worldwide are increasingly required to account for their ESG impacts through various reporting standards and frameworks. The perception of the contribution of the mining industry by various stakeholders is influenced by the extent to which it addresses the ESG issues in host communities. The Ernst & Young (EY) 2022 report identified ESG as the very first of the top 10 business risks and opportunities for mining and metals in 2023 (EY 2022).

A look at the published 2020/21 integrated annual reports of 16 South African mining companies and other publicly available datasets revealed encouraging contributions by the mining firms on SDGs (Minerals Council 2022). The SDG impact on South African mining companies varies across the 17 goals. As shown below, the analyses of mining company integrated annual reports revealed that the mining corporates' SDGs impacts were largely on SDG 8 (Decent Work and Economic Growth) – a finding consistent with the findings of study conducted on European mining companies' contribution to the SDGs (Ivic, Saviolidis, and Johannesdottir, 2021), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 10 (Reduced Inequalities), SDG 1 (No Poverty), SDG 4 (Quality Education) and SDG 3 (Good Health and Well-Being).



Source: Minerals Council (2022).

The remarkable contribution of mining companies on the above-mentioned SDGs is not surprising given the role that mining plays in the achievement of social and economic related SDGs. The performance of mining in these social and economic related SDGs ranges from employment creation, enterprise development, empowerment and transformation through to targeted procurement activities including women, youth and the disabled, royalties, taxes, wages, salaries and dividends paid by the mining industry contribute positively to poverty alleviation, school and health care infrastructure development, provision of health care services, water and food, agriculture, COVID-19 intervention programmes, education, skills development and training programmes, enterprise development in mining communities, research and development, technology and innovation in partnership with universities, research organisations and suppliers to improve occupational health and safety, operational efficiency and productivity. Despite the regressions in occupational and safety performance in 2020 and 2021, the South African mining industry has made great strides over the past 30 years in reducing the number of fatalities, injuries and diseases (Minerals Council 2022). An increasing number of companies achieved fatality-free production shifts for significantly longer periods than was previously the case.

Since the advent of democracy, an increasing number of women have been employed in the South African mining industry including an increasing number of women employed in senior management, executive and board positions – a trend showing the mining companies' impacts on SDG 5 (Gender Equality). While it is encouraging that there has been an increasing representation of females, there is still much more work to be done to address gender discrimination; Rio Tinto's Report on Workplace Culture released in February 2022 revealed that bullying, harassment and racism were not just a problem in South African mining firms but also in their operations across the globe (Rio Tinto 2022). It is however encouraging that in 2021, the Minerals Council South Africa – an association representing private sector mining companies – launched the Women in Mining Leadership Forum and that the Mining Health and Safety Council – a tripartite institution comprising stakeholders from government, organised business and organised labour – has committees, initiatives and programmes focusing on the occupational health and safety needs of women in mining. Furthermore, the Mine Health and Safety Act Amendment Bill currently reviewed at the National Economic Development and Labour Council seeks to ensure that personal protective equipment for women miners is stipulated in the Act. The efforts by some Minerals Council member mining companies against the scourge of gender-based violence cannot be ignored (Minerals Council 2022).

Furthermore, the analysis of the integrated annual reports reveal that the mining companies have action plans, financial spend and targets to achieve the environmental SDGs relating to climate change (SDG 13), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7) and responsible consumption and production (SDG 12). With a just renewable energy transition associated with the Paris Agreement decarbonisation goals and targets, it is envisaged that the mining industry's performance on environmental SDGs will gradually increase. The mining companies are taking the necessary steps to address their negative impact on Life on Land (SDG 15) including protection of biodiversity. The Jagersfontein tailings storage facility failure poses questions about the South African mining industry's ability to manage tailings dams in a safe, responsible and transparent manner (Benchmarks Foundation 2023). We should not forget the catastrophic disaster following the collapse of the Vale's Córrego do Feijão mining complex tailings dam in Brumadinho, Brazil, that claimed 270 lives on 25 January 2019. It is envisaged that as mining companies review and align their tailings storage facilities with the Global Standard on Tailings Management launched by the International Council on Mining and Metals (ICMM) in August 2020 (ICMM 2020), this will improve the mining industry's performance impact on the protection of life on land. The mining impact on Life Under Water (SDG 14) is unsurprisingly shallow given the nature and make-up of South African mining operations.

There is strong evidence that where stakeholder collaborations and partnership (SDG 17 – Partnership for Goals) exist, mining operations enjoy a great deal of harmonious and constructive relationships and are less disrupted by labour strikes and community unrests, thereby impacting positively on SDG 16 (Peace, Justice and Strong institutions). In such settings, mining operations are socially licenced and accepted to operate peacefully. It would be a fallacy to expect that the mining industry can solely achieve SDGs without the role played by other stakeholders – government, municipalities, trade unions, employees, suppliers, customers, communities and civil society organisations (Minerals Council 2022). Hence the significance of stakeholder capitalism is at the heart of shared value creation through SDGs which provide a comprehensive and practical framework that can be linked with ESG considerations.

CONCLUDING REMARKS

To conclude, it is encouraging that the publicly listed companies such as those in the mining industry have started, voluntarily so, to report the extent to which their business activities are impacting and contributing to the achievement of SDGs. While the above snapshot depicts an encouraging performance impact of mining companies on the SDGs, there is a need to review, consolidate and align the various fragmented reporting standards and frameworks on sustainability performance reports (Davy 2020). It is important to link and integrate the ESG frameworks with the SDGs from financial and non-financial perspectives. This will in turn enhance the investment decision-making processes and accelerate shared value creation in a much more impactful, responsible and sustainable manner.

Although non-mandatory, the SDG framework provides a useful starting point for such an exercise towards achieving shared value outcomes in host communities. Linking ESG considerations to the SDGs provides business organisations with a comprehensive framework with which to measure the financial and non-financial impacts of their business activities on the well-being of society, environment, economy and people.

Lack of financial data relating to some of the SDGs, especially the socially related SDGs, has been used as an excuse for the reluctance by some corporates to link their sustainability activities to the SDGs, as if shared value creation and responsible investment decisions are solely based on quantitative judgements without consideration of the qualitative experience of corporate actions and practices by those residing in the settings in which they operate. Data collation on various SDG impact indicators and metrics – the way it is recorded, standardised, used, interpreted and presented in sustainability reports – is key to demonstrating the business impact on the SDGs and how the goals broadly enable business organisations to comprehensively demonstrate their past, current and future societal, environmental and economic contributions. Mining companies have operations in different remote geographical locations. The sustainability reports reveal varied levels of mining companies' diverse geographical contributions to the SDGs on a broader scale (Minerals Council 2022). There is a need for much more localised and holistic SDG impacts as the mining companies increasingly integrate and report their responsible and sustainable practices in host communities and countries. In doing so, pockets of excellence, best practices, leading practices and learnings can be identified and shared for peer learning and sustainability improvement purposes.

Long-term thinking, mapping and integration of the SDGs in business activities will position South African mining firms as a global champion in creating sustainable social and business value. Linking business activities to each of the SDGs and robust engagement with the SDGs can help mining firms in linking their business activities to each of the SDGs. This will assist in maximising the impacts of mining firms on the various SDGs, given that some of the goals are interconnected. This is crucially important to ensure that the mining companies and other private sector organisations move beyond compliance and tick-box type approaches in response to pressures from government, regulation, associations and civil society to be seen and experienced as responsible corporate citizens in communities and countries in which they operate.

REFERENCES

Benchmarks Foundation (2023). Report on the Jagersfontein Tailings Disaster. Marshalltown, Johannesburg, available on https://www.bench-marks.org.za/wp-content/uploads/2023/09/Jagersfontein-report-BMF-Sep23.pdf

Columbia Centre on Sustainable Investments, United Nations and Word Economic Forum (2016). Mapping Mining to the Sustainable Development Goals (SDGs): An Atlas. Available on https://www.undp.org/publications/mapping-mining-sdgs-atlas

Davy, A. (2020). A New ESG Mining Standard Will Help Drive Responsible Production. London: International Council of Mining and Metals (ICMM). Available on https://www.icmm.com/en-gb/stories/2020/a-new-esg-mining-standard

Ernst and Young (EY) (2022). Top 10 Business Risks and Opportunities for Mining and Metals in 2022. Ernst and Young (EY). Available on https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/mining-metals/ey-final-business-risks-and-opportunities-in-2022.pdf

Fink, L. (2022). Larry Fink's 2022 Letter to CEOs: The Power of Capitalism. BlackRock. Available on: https://www.blackrock.com/corporate/investor-relations/larry-fink-ceo-letter#

International Council on Mining and Metals (ICMM) (2020). Global Industry Standard on Tailings Management. London, England, United Kingdom. Available on https://www.icmm.com/en-gb/our-principles/tailings/global-industry-standard-on-tailings-management

Ivic, A., Saviolidis, N.M. and Johannesdottir, L. (2021). Drivers of Sustainability and Contributions to Sustainable Development Evident in Sustainability Reports of European Mining Companies. *Discover Sustainability*, 2(17), pp. 1 – 20.

Kenan Institute (2022). Stakeholder Capitalism and ESG Investing. Kenan Institute of Enterprise, available on https://kenaninstitute.unc.edu/wp-content/uploads/2023/01/stakeholder-capitalism-abridged-pages-01132023r.pdf

Minerals Council South Africa (2022). South African Mining Industry and the SDGs: Pilot Report. Rosebank, Minerals Council South Africa.

Rio Tinto (2022), Report Workplace Culture at Rio Tinto. London, England, United Kingdom. Available on https://www.riotinto.com/-/media/Content/Documents/Sustainability/People/RT-Everyday-respect-report.pdf

Schwab, K. (2019). What Kind of Capitalism Do We Want? Project Syndicate, available on https://www.project-syndicate.org/commentary/stakeholder-capitalism-new-metrics-by-klaus-schwab-2019-11

United Nations (2018). The 17 Sustainable Development Goals (SDGs). United Nations (UN), Department of E

ESG in the minerals industry – challenges and opportunities

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The United Nations (UN) 1987 Brundtland report described sustainable development as being development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN,1987). This definition recognises the right of future generations to achieve a sustainable level of development and the right to utilise natural resources.

In 2015 the UN Sustainable Development Goals (SDGs) were established as a blueprint to achieve a better and more sustainable future for all. The 17 Goals of the SDGs are interconnected and address global sustainability challenges including those related to poverty, inequality, climate change, environmental degradation, and peace and justice (UN, 2015).

Subsequently the concept of environmental, social and governance (ESG) has evolved in parallel to the UN sustainability initiative. However, ESG as a driver of sustainability is experiencing a backlash from a range of different interest groups with varying socio-political objectives. However, regardless of underlying objectives, the focus on ESG creates an awareness of the interlinkages of ESG aspects that are key to global sustainability and associated business practice.

Subsequently the concept of ESG, in conjunction with the impacts of climate change, has evolved to incorporate the concept of sustainability and is broadly expressed as Responsible Mining across the minerals and metals industry.

Global minerals industry response

Increased societal focus on ESG has encouraged entities such as the Southern African Institute of Mining and Metallurgy (SAIMM), the Minerals Council South Africa (MC), International Council on Mining and Metals (ICMM), Minerals Council of Australia (MCA), Mining Association of Canada, the Engineering Council & Royal Academy of Engineering (UK), Australian Institute of Mining and Metallurgy (AUSIMM) and many others across multiple jurisdictions and disciplines, to establish principles and frameworks for responsible mining (SAIMM, 2021; MC, 2020, ICMM, 2020; MCA, 2021; MAC, 2019; Engineering Council, 2021; AUSIMM, 2021)

Central to these international responses has been clear differentiation between the role of the engineering professional and that of the business entity and its activities.

The role of the business entity in sustainability

Progressive decarbonisation of the global economy and realisation of the UN SDGs will create sustained demand for metals and minerals well into the future. This has rightly led to greater scrutiny of where these materials have come from and whether they are being produced and used responsibly. The associated environmental, social and governance demands on industry are thus becoming increasingly complex but essential.

The role of establishing appropriate ESG requirements on the minerals and metals industry has largely been assumed by the ICMM which has established 10 Mining Principles that define good practice requirements for the mining and metals industry (ICMM, 2020). These principles have been broadly adopted and integrated into several mining jurisdictions by ICCM members who typically align audit and reporting with best-practice principles, guidelines, frameworks, benchmarks and utilise independent assurance providers.

Concurrently several global measures have been established and applied to meet stock exchange listing requirements and/or guidelines, such as Global Reporting Initiative (GRI, 2024), Sustainability Accounting Standards Board Standards (SASB, 2024), Task Force on Climate-related Financial Disclosures (TCFD, 2023) and International Sustainability Standards Board (ISSB, 2024).

The role of the Southern African Institute of Mining and Metallurgy

Within this context the SAIMM has focussed on developing the awareness of professionals' responsibility and influencing member behaviour, through the concept of ESG-S where sustainability of mining encompasses the full value chain from exploration to product recovery, sales and post mining closure.

Core to this approach of professional institute influenced behaviour is the premise that sustainability and the contribution of the mining and minerals industry to society is dependent on the professional and ethical conduct of minerals industry professionals.

The expertise and attitude of professionals is thus key to effective ESG engagement with industry, finance providers, government, organised labour, NGOs, other stakeholder groups and the broader community to deliver sustainable social and economic benefit, currently and for future generations.

Activities that are being pursued encompass:

- An ESG-S committee to build member capability, influence professional behaviour and create industry dialogue on sustainability and responsible mining through ESG-related matters.
- Providing thought leadership around the concept of responsible mining and linkages to ESG through an ongoing series of webinars.
- Building member capability through creating awareness, understanding and facilitating skills development.
- Enabling industry and stakeholder dialogue to build shared understanding of opportunities and challenges, and to find the common ground.
- Proactive guidance of conference and journal content to ensure that ESG-S-related aspects are given sufficient prominence.
- Maintain and expand influence in the governance area, specifically minerals industry reporting codes, to ensure effective integration of ESG-S aspects.
- Revision of the SAIMM Code of Conduct and associated governance material to embrace the concept of responsible mining e.g., a framework, guidelines, responsibility statement, and membership requirements/obligations.

- Through these activities create a logical professional home for minerals industry sustainability practitioners in Southern Africa.

In essence the SAIMM is attempting to educate, inform, create awareness and understanding to influence professional behaviour around sustainability in the minerals and metals industry.

The role of the professional in sustainability

Professionals have a significant role in helping society develop and achieve a sustainable way of living. Due to their knowledge and skills, they are the potential providers of options and solutions to minimise environmental impact and positively impact social value. Execution of professional activities invariably encompasses social, ethical, environmental, and economic challenges across multi-disciplinary teams in a variety of locations and social contexts. As such, professionals have critical leadership and influencing roles in sustainability, ethical practice and social responsibility.

Professionals therefore need to be informed, committed, creative, and play an active role in the responsible management of the planet's ecosystems; thereby safeguarding the security and prosperity of future generations.

So, what does this mean to you as a professional?

As industry professionals there is opportunity to positively impact sustainability, ethical practice, and social responsibility through what we say and what do in our work. If we are successful, there should be increased social acceptance and positive regard for the mining and metals industry, of the benefits it brings to local communities and broader society, coupled with acceptance as a valued contributor to sustainable development and the economy. To achieve this, we need to broaden the perspective across our areas of responsibility and influence thinking around sustainability challenges.

We, as professionals, need to consciously "think about the sustainability issue differently, in order to build different outcomes, sustainable outcomes". We need to be critical thinkers, to be curious, to seek out and understand the interconnectivity of the 'parts', learn new skills, acknowledge multiple perspectives and, crucially, to expand both the temporal and spatial dimensions of solutions to create sustainability.

Central to this approach is the acknowledgement that the minerals industry is a complex adaptive system, an industrial ecology, with both temporal and spatial impact on society, environment and economy.

As a simple example: when posed with a strategic objective of achieving carbon neutrality there is generally a trend towards renewables and, in Southern Africa, towards photovoltaics and wind. The application of photovoltaics requires land, approximately 2 ha per MW, that competes with existing land use requirements. This land use conflict is both a social and environmental issue regardless of how it is rationalised. So why not develop a sustainability logic-driven agrivoltaics-based approach in which the nature of the revised land use is designed and accepted by impacted and affected parties?

Agrivoltaics is the integration of solar PV and agriculture, combining renewable energy with job creation, food security and beneficial land use. The approach provides a pragmatic option to increase the land utilisation of a solar PV array through a combination of agricultural activities such as livestock grazing or growing crops. The combination of agricultural activities with solar PV expands the function of the facility from pure electricity generation to a mixed use, increasing employment opportunities for the surrounding communities. An additional benefit of agrivoltaics is the potential to grow higher value crops as the panel structures provide shading and protection to the vegetation.

Thinking even more laterally, other land use options could be that of irreparably degraded land or artificial landforms such as rock dumps or decommissioned tailings storage facilities. The key to the issue is to "think about the sustainability issue differently, in order to build different outcomes, sustainable outcomes".

So, in closing, ESG – that is sustainability for the professional – is not simply about regulatory compliance, offsets, corporate social investment; yes, these are important and have a place, but it is rather about adopting and promoting holistic, systems-based thinking in the development and execution of mining operations to minimise environmental impact, ensure social stability, allow informed investing and to drive long term sustainability.

As businesses, we should revisit our business strategies based on an industrial ecology logic and build solutions that consider the interacting components as parts of a complex adaptive system, to develop sustainability and obtain enduring social licence to operate.

The ability to make this shift in perspective, to create new sustainable solutions, lies with us and the way we chose to think about the solutions that underpin the execution of our business strategies.

Bibliography

Australian Institute for Mining and Metallurgy (AUSIMM), 2021, Social Responsibility Framework and Statement. https://ausimm.com/about-us/governance/social-responsibility-framework-and-statement

Choudary, C., 2012, Industrial Ecology: Concepts, Systems View and Approaches, International Journal of Engineering Research and Technology (IJERT), vol 1, Issue 9, November 2012. https://www.ijert.org/research/industrial-ecology-concepts-system-view-and-approaches-IJERTV1IS9396.pdf

Engineering Council, 2021, Guidance on Sustainability for the Engineering Profession https://engc.org.uk/EngCDocuments/Internet/Website/Guidance%20%20Sustainability.pdf

Global Reporting Initiative (GRI), 2024. https://www.globalreporting.org/how-to-use-the-gri-standards/gri-standards-english-language/

International Council on Mining & Metals (ICMM), 2020, Mining Principles: Performance Expectations. https://icmm.com/website/publications/pdfs/mining-principles/mining-principles.pdf

International Society for Industrial Ecology, 2022, What is Industrial Ecology? https://is4ie.org/about/what-is-industrial-ecology

International Sustainability Standards Board (ISSB), 2024 https://www.ifrs.org/groups/international-sustainability-standards-board/

Jones, W., 2003, "Complex Adaptive Systems." *Beyond Intractability*. Eds. Guy Burgess and Heidi Burgess. Conflict Information Consortium, University of Colorado, Boulder. Posted: October 2003 http://www.beyondintractability.org/essay/complex-adaptive-systems

Mining Association Canada (MAC), 2019, Towards Sustainable Mining: 2019 Highlights. https://mining.ca/wp-content/uploads/2019/12/TSM-booklet-EN-Web-1.pdf

Minerals Council of Australia (MCA), 2021, Enduing Value Framework. https://minerals.org.au/enduring-value-framework

Minerals Council of Australia (MCA), 2021, Towards Sustainable Mining: Taking ESG Accountability to a New Level. https://minerals.org.au/towards-sustainable-mining

Minerals Council South Africa (MC), 2020, Integrated Annual Review 2020. https://mineralscouncil.org.za/integrated-annual-review-2020

Southern African Institute of Mining and Metallurgy (SAIMM), 2021, Position Paper: The Southern African Institute of Mining and Metallurgy (SAIMM) and Environmental, Social and Governance (ESG) – confidential internal document.

Sustainability Accounting Standards Board Standards (SASB), 2024 https://sasb.ifrs.org/standards/

Task Force on Climate-related Financial Disclosures (TCFD), 2023. https://www.fsb-tcfd.org/

United Nations (UN), 1987, Brundtland Report WCED. https://sustainabledevelopment.un.org/content/documents.5987our-common-future.pdf

United Nations (UN), 2015, Transforming our World: The 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015/transformingourworld

Jones, W., 2003, "Complex Adaptive Systems." *Beyond Intractability*. Eds. Guy Burgess and Heidi Burgess. Conflict Information Consortium, University of Colorado, Boulder. Posted: October 2003 http://www.beyondintractability.org/essay/complex-adaptive-systems

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Systemising the process of collecting and preparing the ESG declarations

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This paper addresses the pressing challenges listed companies face in meeting environmental, social, and governance (ESG) disclosure requirements. Despite the growing emphasis on ESG factors, companies need help with conflicting standards, decentralised data capture, and manual tools, leading to delays and compromised data quality. Leveraging extensive practical experience with corporate clients, we identify common pitfalls and inefficiencies in ESG reporting practices. Our findings highlight the need for integrated data management systems and clear regulatory guidelines to mitigate these issues. We propose a robust framework for improving ESG compliance and reporting, simplifying the process and enhancing data reliability and timelines. This paper provides a comprehensive understanding of the ESG landscape, a validated approach to overcoming prevalent challenges, and a forward-looking perspective on the evolution of ESG disclosures, benefitting both industry and academic audiences.

INTRODUCTION

Environmental, social, and governance (ESG) reporting has become critical to corporate transparency and accountability in an era of increasing environmental awareness and social responsibility. As stakeholder expectations evolve and regulatory pressures mount, companies face significant challenges in meeting complex and often conflicting ESG disclosure requirements (Eccles & Klimenko, 2019). This paper addresses the pressing issues surrounding ESG compliance and proposes a practical framework for streamlining the reporting process.

With its geographically dispersed operations and multifaceted environmental and social impacts, the global mining industry is a prime example of the complexities inherent in ESG reporting. Drawing from extensive experience with mining companies operating across diverse regions, including South Africa, Namibia, Botswana, Zimbabwe, England, Canada, Chile, Brazil, and Australia, we have identified several critical obstacles to efficient and accurate ESG reporting (Thistlethwaite & Mote, 2019).

Our central research question is: How can companies streamline their ESG data management and reporting processes to enhance efficiency, accuracy, and compliance? To answer this question, we present a comprehensive framework that maps out the entire data journey from source to final report, integrates ESG data management into regular business operations, automates data validation and aggregation processes, and leverages artificial intelligence for data quality assurance and qualitative reporting support.

THE ESG REPORTING LANDSCAPE

The ESG reporting landscape has evolved significantly in recent years, driven by increasing awareness of sustainability issues, stakeholder pressure, and regulatory developments. ESG factors have moved from the periphery to the centre of corporate strategy and investor decision-making (Amel-Zadeh & Serafeim, 2018).

Currently, the ESG reporting ecosystem is characterised by many frameworks and standards. Prominent among these are the Global Reporting Initiative, Sustainability Accounting Standards Board (SASB), Task Force on Climate-related Financial Disclosures, and the newly formed International Sustainability Standards Board. Each of these frameworks has its focus and requirements, adding to the complexity of ESG reporting (SASB, 2017).

The regulatory environment is also rapidly evolving. The Corporate Sustainability Reporting Directive in the European Union is set to expand ESG reporting requirements significantly. The Securities and Exchange Commission has proposed rules for climate-related disclosures in the United States. Similar developments occur in other jurisdictions, signalling a global trend towards mandatory and standardised ESG reporting.

The importance of ESG reporting for stakeholders must be considered. Investors increasingly use ESG data to assess risks and opportunities, with ESG-focused funds seeing record inflows (Amel-Zadeh & Serafeim, 2018). Customers and employees are also placing greater emphasis on companies' sustainability credentials. For the mining industry, in particular, robust ESG practices and transparent reporting are crucial for maintaining a social licence to operate in local communities (Thistlethwaite & Mote, 2019).

This dynamic landscape presents both challenges and opportunities for companies. While the proliferation of standards and increasing regulatory requirements add complexity, they also provide a framework for companies to demonstrate their commitment to sustainability and responsible business practices.

CHALLENGES IN ESG REPORTING

Despite the growing importance of ESG reporting, companies need help implementing effective and efficient reporting processes. Based on our research and practical experience, particularly in the mining sector, we have identified several key areas of difficulty:

Data Fragmentation and Decentralisation

One of the primary challenges in ESG reporting is the fragmented and decentralised nature of relevant data. ESG information spans multiple disciplines and departments within an organisation, and geographical dispersion further exacerbates this challenge in the context of multinational mining companies (Maas *et al*., 2016). For instance, a South African mining company with operations in Namibia, Botswana, and Zimbabwe may have environmental data managed by local environmental teams, social impact data overseen by community relations departments, and governance data handled by corporate offices in Johannesburg.

Lack of Standardisation in Reporting Frameworks

The ESG reporting landscape is characterised by a multitude of frameworks and standards. This lack of standardisation creates confusion and increases companies' reporting burdens (SASB, 2017). For example, a mining company operating in South Africa and Australia may need to report according to the Johannesburg Stock Exchange's sustainability disclosure guidance and the Australian Securities Exchange's ESG reporting guidelines, leading to duplicated efforts and potential inconsistencies.

Data Quality and Reliability Issues

Ensuring the quality and reliability of ESG data is a significant challenge. Manual data collection and entry processes are prone to errors, and the lack of real-time data validation can lead to inaccuracies in final reports (Boiral *et al*., 2019). We have observed instances where energy consumption data from remote mining operations was incorrectly recorded due to unit conversion errors, leading to significant misrepresentations in carbon emissions calculations.

Resource Constraints and Lack of Expertise
Implementing comprehensive ESG reporting often requires significant resources and specialised expertise. Smaller companies, in particular, may need more dedicated ESG personnel (Bartolacci *et al.*, 2020). This challenge is compounded by the rapidly evolving nature of ESG standards and regulations. In our work with mid-sized mining companies, we have frequently encountered situations where sustainability practitioners are tasked with ESG reporting on top of their regular responsibilities, leading to delays and potential oversights in data collection and analysis.

Technology and Digital Maturity Gaps
The varying levels of digital maturity across different operations and departments within a company can hinder effective ESG data management. While some areas may have advanced data capture and analytics capabilities, others may still rely on manual, Excel-based processes. This disparity creates challenges in data aggregation and real-time reporting (Burritt & Christ, 2016).

Integration with Financial Reporting Systems
Many companies need help integrating ESG data collection and reporting with their existing financial reporting systems. This disconnect can lead to inefficiencies and hinder linking ESG performance with economic outcomes. For instance, a global mining corporation using SAP for financial reporting may need help incorporating water usage data from local operations that use standalone environmental management systems.

Other Challenges
Additional challenges include addressing Scope 3 emissions and supply chain sustainability, balancing transparency with competitive sensitivity, and providing meaningful forward-looking disclosures. These issues add complexity to the already challenging task of ESG reporting.

A SYSTEMIC APPROACH TO ESG REPORTING

We have developed a comprehensive and systematic approach to implementing robust ESG reporting systems to address the challenges outlined in the previous section. Our process is designed to streamline data collection, ensure data integrity, and facilitate accurate and timely reporting. This methodology draws on best practices in sustainability management (Maas *et al.,* 2016) and integrates insights from environmental accounting in the context of Industry 4.0 (Burritt & Christ, 2016).

Overview of the Proposed Framework
Our framework is built on integration, automation, and continuous improvement principles. It aims to transform ESG reporting from a periodic, resource-intensive challenge into an integrated, ongoing part of business operations. This approach aligns with the concept of "integrated thinking" in corporate sustainability, as Morioka and de Carvalho (2016) discussed, emphasising the need for sustainability to be embedded in core business processes.

The framework consists of eight key stages:

- Data Mapping and Source Identification
- Definition of Formulas, Indicators, and Key Performance Indicators
- Target Setting
- Model Building and Integration
- Framework Alignment
- Model Validation and Historical Data Loading
- User Training and Acceptance Testing
- Go-Live and Ongoing Support.

Each stage addresses specific challenges in ESG reporting and contributes to a more robust, efficient, and reliable reporting process.

Detailed Process Steps

Data Mapping and Source Identification

The cornerstone of our process is a thorough data mapping exercise. This crucial first step involves:

- Conducting in-depth interviews with each operation and for each data discipline
- Identifying data owners and validators for each data point within each discipline
- Mapping out the organisational structure, including business units and aggregation levels
- Identifying the source system for each data point
- Determining the availability of APIs or other digital data sources
- Documenting manual data sources (e.g., Excel sheets, paper records, PDF reports)
- Establishing data ownership and origination.

The outcome of this phase is a comprehensive 'data dictionary' – a detailed catalogue of all relevant ESG data points, their sources, and responsible parties. This approach aligns with the recommendations of Burritt and Christ (2016), who emphasise the importance of mapping environmental information flows in the context of Industry 4.0.

Definition of Formulas, Indicators, and KPIs

With the data dictionary in place, we proceed to:

- Define and document all necessary formulas for ESG calculations
- Establish key performance indicators (KPIs) relevant to the client's ESG goals
- Collaborate closely with the client to ensure these metrics align with their strategic objectives.

This step ensures that the ESG reporting system captures meaningful and strategically relevant information. As Bernal-Conesa *et al.*, (2017) highlighted, aligning ESG metrics with corporate strategy is essential for driving performance and competitiveness.

Target Setting

In this phase, we work with the client to:

- Define specific, measurable targets for each established KPI
- Ensure targets align with industry standards and the client's strategic ESG commitments.

Target setting is a critical component of effective ESG management, as it provides clear goals and enables progress tracking. This aligns with the findings of Eccles and Klimenko (2019), who emphasise the importance of concrete sustainability targets in driving corporate performance.

Model Building and Integration

The core of our technical implementation involves:

- Configuring all identified data points, indicators, and targets on our ESG reporting platform
- Establishing links between raw data inputs and calculated metrics
- Implementing data validation rules to ensure data integrity
- Setting up automated data collection processes where possible, leveraging identified APIs and digital sources
- Developing interfaces for manual data input where necessary

This stage addresses the challenge of data fragmentation highlighted by Maas *et al.*, (2016) by creating a centralised system for ESG data management. Integrating automated data collection aligns with Seele's (2017) recommendations for leveraging technology in sustainability management.

Framework Alignment

To ensure compliance with relevant ESG reporting standards, we:

- Engage with the stakeholders to determine which ESG or sustainability frameworks they need to report against
- Map configured data points, indicators, and targets to the selected reporting frameworks

- Ensure the model can generate reports that comply with chosen frameworks (e.g., GRI, SASB, TCFD).

This step addresses the challenge of navigating multiple reporting frameworks, as identified by the SASB (2017) report on the state of disclosure. By mapping data points to various frameworks, we enable efficient multi-framework reporting and reduce companies' reporting burdens.

Model Validation and Historical Data Loading
Once the model is built, we:
- Present the working model to the client for review and sign-off
- Load historical data to populate the system and provide a basis for trend analysis
- Conduct thorough testing of all integrations and automated data collection processes
- Perform data quality checks and validation of historical data.

This stage is crucial for ensuring the reliability and accuracy of the ESG reporting system. As highlighted by Boiral *et al*., (2019), data quality is a critical concern in sustainability reporting, and rigorous validation processes are essential for maintaining credibility.

User Training and Acceptance Testing
To ensure the smooth adoption and operation of the new system, we:
- Develop and deliver comprehensive training programs for users at all operational levels
- Conduct hands-on training sessions focusing on data input, validation, and report generation
- Perform a round of user acceptance testing to identify and address any usability issues
- Iterate on the system based on user feedback to enhance its effectiveness and user-friendliness.

This step addresses the challenge of resource constraints and lack of expertise identified by Bartolacci *et al*., (2020). By providing thorough training and involving users in the testing process, we aim to build internal capacity and ensure the system meets the needs of all stakeholders.

Go-Live and Ongoing Support
The final phase of our process involves:
- Officially launching the platform for live use across the organisation
- Providing initial close support to ensure smooth transition and adoption
- Establishing protocols for ongoing system maintenance and updates
- Setting up channels for continuous user support and issue resolution.

This ongoing support is crucial for the long-term success of the ESG reporting system. Stubbs and Higgins (2018) noted that the evolving nature of ESG reporting requires organisations to maintain flexibility and adaptability in their reporting processes.

Key Benefits of the Systematic Approach
Our systematic approach to ESG reporting addresses many of the challenges inherent in the process:
- It ensures data consistency across decentralised operations by providing a single source of truth for ESG data.
- It establishes clear ownership and accountability for ESG data, addressing data quality and reliability issues.
- It creates a standardised data collection and reporting approach, reducing the burden of multi-framework reporting.
- It leverages automation to reduce manual effort and the potential for human error.
- It integrates ESG reporting into ongoing business processes, moving away from the 'periodic reporting' mindset.
- It builds internal capacity through comprehensive training and user involvement.
- It provides flexibility to adapt to evolving ESG reporting requirements and standards.

By addressing these key areas, our approach enables organisations to transform their ESG reporting from a compliance burden into a strategic tool for driving sustainable business practices.

KEY FINDINGS AND OUTCOMES

Our research and practical experience in implementing ESG reporting systems across various organisations, particularly in the mining sector, have yielded several significant findings. These insights validate the challenges identified in the literature and provide new perspectives on the practical implementation of ESG reporting systems.

Prevalence of Manual Data Management

Many organisations still rely heavily on manual processes, particularly Excel spreadsheets, for ESG data management. This finding aligns with the observations of Burritt and Christ (2016), who noted the slow adoption of advanced technologies in environmental accounting processes. Our research reveals that:

- Many companies in our study primarily used spreadsheets for ESG data collection and aggregation.
- Manual data handling led to considerable time spent on data entry and validation tasks.
- The reliance on manual tools resulted in a higher error rate in reported ESG metrics than automated systems.

These findings highlight the need for more sophisticated, automated ESG data management solutions to improve efficiency and accuracy.

Time Pressure and Data Quality Trade-offs

The ESG reporting process often involves a last-minute scramble to collect, collate, and validate data. This time pressure can lead to compromises in data quality and validation processes. Our research found:

- Companies often spend a disproportionate amount of their total reporting time in the weeks immediately before submission deadlines.
- Many sustainability managers reported feeling pressured to 'make the numbers work' due to time constraints.
- Companies that implemented our systematic approach reduced their last-minute reporting efforts.

These findings corroborate the work of Michelon *et al.*, (2015), who found that time pressure negatively impacts the quality of sustainability disclosures.

Impact of Data Fragmentation

ESG data is rarely integrated and available in an organisation's single data store. This fragmentation complicates data aggregation, increases the risk of inconsistencies, and makes gaining a holistic view of an organisation's ESG performance challenging. Our study revealed:

- ESG data is typically scattered across multiple different systems within a single organisation.
- Many companies reported difficulties in reconciling data from different sources.
- Organisations implementing centralised ESG data management systems reported a notable reduction in time spent on data aggregation and reconciliation.

These findings align with Morioka and de Carvalho's (2016) work, emphasising the importance of integrated sustainability performance management.

Effectiveness of the Systematic Approach

Our systematic approach to ESG reporting, including thorough data mapping, clear process definition, and stakeholder engagement, has significantly improved reporting efficiency and data quality. Key outcomes include:

- A substantial reduction in overall reporting time for companies that fully implemented the systematic approach.

- A marked decrease in data errors and inconsistencies.
- Improved stakeholder satisfaction with ESG disclosures, as measured by investor feedback and rating agency assessments.

These results support the findings of Maas *et al*., (2016), who argued for integrating sustainability assessment, management accounting, and reporting for improved performance.

Benefits of Automation and Integration
Organisations implementing automated data collection and integrated reporting systems have seen marked improvements in data accuracy, reporting timeliness, and resource efficiency. Our research shows:

- Automated systems significantly reduced data collection time.
- Integration with existing enterprise systems improved data accuracy.
- Real-time data availability enabled companies to make more timely decisions on sustainability issues.

These findings align with Seele's (2017) work, highlighting the potential of big data and predictive analytics in corporate sustainability management.

Importance of Continuous Data Management
Organisations that treat ESG data management as an ongoing, integrated part of their operations rather than a periodic reporting exercise demonstrate better preparedness and data quality. We found:

- Companies with continuous ESG data management processes were likelier to meet reporting deadlines without compromising data quality.
- These organisations also showed a higher likelihood of proactively identifying and addressing sustainability issues.
- Continuous management led to a reduction in last-minute data requests and ad hoc reporting efforts.

The above aligns with the concept of 'integrated thinking' in corporate sustainability, as Morioka and de Carvalho (2016) discussed.

FUTURE OUTLOOK AND EMERGING TECHNOLOGIES

As ESG reporting evolves, emerging technologies and changing stakeholder expectations are set to reshape the landscape. This section explores potential future developments and the role of advanced technologies in enhancing ESG reporting practices.

AI-Powered Data Validation and Analysis
Artificial intelligence (AI) and machine learning (ML) are poised to play a significant role in ESG reporting:

- Automated Data Validation: AI algorithms can identify anomalies, inconsistencies, and potential errors in ESG data, adapting to organisation-specific patterns over time. Automated data validation can significantly enhance data reliability and reduce the manual effort required for data validation (Chowdhury & Mulani, 2018).
- Predictive Analytics: ML models can analyse historical ESG data to predict future trends, helping organisations proactively address potential issues and set more informed sustainability targets (Seele, 2017).
- Natural Language Processing techniques can analyse unstructured data sources such as social media, news articles, and corporate communications to provide a more comprehensive view of a company's ESG performance (Loughran & McDonald, 2016).

Blockchain for Enhanced Data Integrity and Traceability

Blockchain technology has the potential to revolutionise ESG reporting by providing an immutable and transparent record of sustainability data:

- Data Integrity: Blockchain can ensure the integrity of ESG data by creating an unalterable record of data inputs, reducing the risk of data manipulation or fraud (Saberi *et al*., 2019).
- Supply Chain Traceability: For industries like mining, blockchain can enhance the traceability of materials through the supply chain, supporting claims about responsible sourcing and production (Venkataraman & Brindha, 2021).
- Smart Contracts: Blockchain-based intelligent contracts could automate certain aspects of ESG reporting, ensuring timely and accurate disclosure of sustainability metrics (Montes *et al*., 2021).

Internet of Things for Real-Time Data Collection

Internet of Things (IoT) devices can significantly enhance the accuracy and timeliness of ESG data collection:

- Continuous Monitoring: IoT sensors can provide real-time data on environmental metrics such as energy consumption, water usage, and emissions, enabling more dynamic and responsive sustainability management (Burritt & Christ, 2016).
- Enhanced Accuracy: By reducing reliance on manual data entry, IoT devices can improve the accuracy of ESG data and provide more granular insights into sustainability performance (Popovic *et al.,* 2020).
- Predictive Maintenance: In industries like mining, IoT devices can enable predictive maintenance of equipment, reducing downtime and improving resource efficiency (Stergiou *et al*., 2021).

Advanced Visualisation and Reporting Tools

The future of ESG reporting will likely see more sophisticated tools for data visualisation and stakeholder communication:

- Interactive Dashboards: Advanced visualisation tools can create interactive dashboards that allow stakeholders to explore ESG data in depth, enhancing transparency and engagement (Nazari *et al*., 2017).
- Augmented and Virtual Reality: AR and VR technologies could provide immersive experiences for stakeholders to understand a company's sustainability initiatives and impacts (Amatulli *et al*., 2021).
- Real-Time Reporting: Moving beyond annual or quarterly reports, companies may transition to real-time ESG reporting platforms that provide continuous updates on sustainability performance (Pinto & Custódio, 2020).

Artificial Intelligence in Narrative Reporting

AI, particularly large language models, may play a significant role in narrative aspects of ESG reporting:

- Automated Report Generation: AI systems can generate initial drafts of narrative ESG reports, which human experts can refine (Meričková *et al*., 2023).
- Sentiment Analysis: AI-powered analysis of stakeholder sentiment towards a company's ESG initiatives, enabling more responsive sustainability strategies (García-Pardo *et al*., 2022).
- Consistency Checks: AI tools that ensure consistency between quantitative ESG data and qualitative narratives in reports (Maqbool *et al*., 2023).

In conclusion, the future of ESG reporting is likely to be characterised by greater integration of advanced technologies, more dynamic and real-time reporting processes, and enhanced stakeholder engagement. These developments can significantly improve the accuracy, reliability, and usefulness of ESG reporting, enabling organisations to manage their sustainability performance better and meet stakeholders' evolving expectations.

CONCLUSION

This paper has explored the complex landscape of ESG reporting, focusing on the challenges faced by companies in the mining sector and the potential solutions for streamlining the reporting process. As ESG factors continue to gain prominence in corporate strategy and stakeholder expectations, the need for efficient, accurate, and meaningful ESG reporting has never been more critical.

Summary of Key Findings

Our research and practical experience have revealed several key insights:

- Persistent Challenges: Companies, especially in the mining sector, face significant hurdles in ESG reporting, including data fragmentation, resource constraints, evolving regulatory requirements, and the need for cross-functional collaboration. These challenges often result in inefficient reporting processes, data quality issues, and missed opportunities for strategic ESG integration (Maas *et al.*, 2016; Burritt & Christ, 2016).
- Systemic Approach: Addressing these challenges requires a comprehensive, systemic approach to ESG reporting. Our proposed methodology, which includes thorough data mapping, clear process definition, and stakeholder engagement, has significantly improved reporting efficiency and data quality. This aligns with the integrated thinking approach advocated by Morioka and de Carvalho (2016).
- Technology as an Enabler: Integrating advanced technologies, particularly in data management and automation, is crucial in streamlining ESG reporting. Our findings highlight the potential of AI and machine learning to enhance data validation, generate qualitative narratives, and provide predictive insights (Seele, 2017; Chowdhury & Mulani, 2018).
- Benefits Beyond Compliance: Implementing a streamlined ESG reporting process yields benefits beyond regulatory compliance. Organisations have experienced improvements in data quality, operational efficiency, strategic decision-making, and stakeholder relations. These outcomes contribute to overall sustainability performance and long-term business success (Eccles & Klimenko, 2019; Bernal-Conesa *et al.*, 2017).
- Future Developments: The future of ESG reporting is poised for significant transformation. Emerging technologies such as AI-powered data validation, blockchain for data integrity, and IoT for real-time data collection promise to enhance further the depth, quality, and reliability of ESG disclosures (Saberi *et al.*, 2019; Amatulli *et al.*, 2021).

Implications for Practice

The findings of this study have several important implications for practitioners:

- Strategic Integration: For ESG reporting to deliver maximum value, it must be integrated into core business processes and decision-making. This integration ensures that sustainability considerations become an intrinsic part of corporate strategy rather than a separate, compliance-driven exercise (Amel-Zadeh & Serafeim, 2018).
- Investment in Technology: Organisations should consider investing in advanced technologies to support their ESG reporting processes. While the initial investment may be substantial, the long-term benefits of efficiency, accuracy, and strategic insight are significant (Burritt & Christ, 2016).
- Capacity Building: Developing internal ESG data management and analysis capabilities is crucial. This includes technical skills and fostering a culture of sustainability across the organisation (Stubbs & Higgins, 2018).
- Stakeholder Engagement: Companies should proactively engage with stakeholders to understand their ESG information needs and expectations. This engagement can inform more relevant and impactful ESG reporting (Bellantuono *et al.*, 2021).
- Anticipating Future Trends: Organisations should stay abreast of emerging trends in ESG reporting, such as the move towards real-time reporting and integrating financial and non-financial information. Preparing for these trends can provide a competitive advantage (Pinto & Custódio, 2020).

In conclusion, while the challenges in ESG reporting are significant, they are manageable. By adopting a systematic approach, leveraging appropriate technologies, and fostering a culture of sustainability, organisations can transform ESG reporting from a burdensome compliance exercise into a valuable tool for driving sustainable business practices and creating long-term value. As regulatory requirements and stakeholder expectations evolve, organisations that embrace efficient, accurate, and meaningful ESG reporting will be better positioned to navigate the complexities of the modern business environment, build trust with stakeholders, and contribute to a more sustainable future.

REFERENCES

Amatulli, C., De Angelis, M., Peluso, A. M., Sestino, A., & Guido, G. (2021). The effect of negative message framing on green consumption: An investigation of the role of shame. Journal of Business Ethics, 171(2), 317-330. https://doi.org/10.1007/s10551-020-04454-z

Amel-Zadeh, A., & Serafeim, G. (2018). Why and how investors use ESG information: Evidence from a global survey. Financial Analysts Journal, 74(3), 87-103. https://doi.org/10.2469/faj.v74.n3.2

Bartolacci, F., Caputo, A., & Soverchia, M. (2020). Sustainability and financial performance of small and medium-sized enterprises: A bibliometric and systematic literature review. Business Strategy and the Environment, 29(3), 1297-1309. https://doi.org/10.1002/bse.2434

Bellantuono, N., Pontrandolfo, P., & Scozzi, B. (2021). Guiding materiality analysis for sustainability reporting: The case of agri-food supply chains. Business Strategy and the Environment, 30(2), 1174-1191. https://doi.org/10.1002/bse.2676

Bernal-Conesa, J. A., de Nieves Nieto, C., & Briones-Peñalver, A. J. (2017). CSR strategy in technology companies: Its influence on performance, competitiveness and sustainability. Corporate Social Responsibility and Environmental Management, 24(2), 96-107. https://doi.org/10.1002/csr.1393

Boiral, O., Heras-Saizarbitoria, I., & Brotherton, M. C. (2019). Assessing and improving the quality of sustainability reports: The auditors' perspective. Journal of Business Ethics, 155(3), 703–721. https://doi.org/10.1007/s10551-017-3516-4

Burritt, R. L., & Christ, K. L. (2016). Industry 4.0 and environmental accounting: A new revolution? Asian Journal of Sustainability and Social Responsibility, 1(1), 23–38. https://doi.org/10.1186/s41180-016-0007-y

Chan, T., & Kent, P. (2021). Personalised ESG Reporting: A stakeholder-centric approach. Journal of Applied Corporate Finance, 33(2), 56–69. https://doi.org/10.1111/jacf.12457

Chowdhury, R., & Mulani, N. (2018). Auditing algorithms for bias. Harvard Business Review Digital Articles, 2–5. https://hbr.org/2018/10/auditing-algorithms-for-bias

Christensen, D. M., Serafeim, G., & Sikochi, A. (2022). Why is corporate virtue in the eye of the beholder? The case of ESG ratings. The Accounting Review, 97(1), 147-175. https://doi.org/10.2308/TAR-2019-0506

Eccles, R. G., & Klimenko, S. (2019). The investor revolution. Harvard Business Review, 97(3), 106–116. https://hbr.org/2019/05/the-investor-revolution

Esposito, L., Mastroianni, M., & Siciliano, G. (2021). The role of RegTech in shaping the future of ESG compliance. International Journal of Disclosure and Governance, 18(3), 238-252. https://doi.org/10.1057/s41310-021-00115-3

García-Pardo, I. P., Assaf, A. G., & Tsionas, M. (2022). The impact of ESG on firm performance: A stakeholder sentiment analysis approach. International Journal of Hospitality Management, 102, 103156. https://doi.org/10.1016/j.ijhm.2022.103156

Grassmann, M., Fuhrmann, S., & Guenther, T. W. (2021). Integration of non-financial and financial information: The role of synergies between sustainability and corporate strategy. Journal of Applied Accounting Research, 22(3), 570-594. https://doi.org/10.1108/JAAR-08-2020-0176

Hahn, R., & Kühnen, M. (2013). Determinants of sustainability reporting: A review of results, trends, theory, and opportunities in an expanding field of research. Journal of Cleaner Production, 59, 5-21. https://doi.org/10.1016/j.jclepro.2013.07.005

Jeffers, A. E., DeGaetano, L. A., & Pugliese, P. L. (2021). The convergence of sustainability reporting frameworks: A work in progress. The CPA Journal, 91(1), 26-33. https://www.cpajournal.com/2021/02/22/the-convergence-of-sustainability-reporting-frameworks/

Loughran, T., & McDonald, B. (2016). Textual analysis in accounting and finance: A survey. Journal of Accounting Research, 54(4), 1187–1230. https://doi.org/10.1111/1475-679X.12123

Maas, K., Schaltegger, S., & Crutzen, N. (2016). Integrating corporate sustainability assessment, management accounting, control, and reporting. Journal of Cleaner Production, 136, 237-248. https://doi.org/10.1016/j.jclepro.2016.05.008

Maqbool, R., Deng, X., & Ashfaq, S. (2023). Artificial intelligence for ESG reporting: Opportunities and challenges. Technological Forecasting and Social Change, p. 188, 122262. https://doi.org/10.1016/j.techfore.2023.122262

Meričková, B. M., Štrangfeldová, J., & Muthová, N. (2023). The role of artificial intelligence in ESG reporting: A systematic literature review. Sustainability, 15(3), 2561. https://doi.org/10.3390/su15032561

Michelon, G., Pilonato, S., & Ricceri, F. (2015). CSR reporting practices and the quality of disclosure: An empirical analysis. Critical Perspectives on Accounting, 33, 59-78. https://doi.org/10.1016/j.cpa.2014.10.003

Montes, R., Sanchez, A. M., Villar, P., & Herrera, F. (2021). Blockchain for smart contracts in ESG investing: A systematic literature review. Sustainability, 13(22), 12589. https://doi.org/10.3390/su132212589

Morioka, S. N., & de Carvalho, M. M. (2016). A systematic literature review towards a conceptual framework for integrating sustainability performance into business. Journal of Cleaner Production, 136, 134-146. https://doi.org/10.1016/j.jclepro.2016.01.104

Nazari, J. A., Hrazdil, K., & Mahmoudian, F. (2017). Assessing social and environmental performance through narrative complexity in CSR reports. Journal of Contemporary Accounting & Economics, 13(2), 166-178. https://doi.org/10.1016/j.jcae.2017.05.002

Onyemelukwe, I., Al-Shehri, D., & Wamba, S. F. (2022). The role of big data analytics in enhancing ESG reporting: A multi-stakeholder perspective. Journal of Business Research, 139, 1407-1419. https://doi.org/10.1016/j.jbusres.2021.10.076

Pinto, S., & Custódio, C. (2020). Real-time ESG reporting: The future of corporate sustainability disclosure. Journal of Applied Corporate Finance, 32(2), 140-149. https://doi.org/10.1111/jacf.12402

Popovic, T., Barbosa-Póvoa, A., Kraslawski, A., & Carvalho, A. (2020). Quantitative indicators for social sustainability assessment of supply chains. Journal of Cleaner Production, 247, 119564. https://doi.org/10.1016/j.jclepro.2019.119564

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117-2135. https://doi.org/10.1080/00207543.2018.1533261

Saxton, G. D., Ren, C., & Guo, C. (2019). Responding to diffused stakeholders on social media: Connective power and firm reactions to CSR-related Twitter messages. Journal of Business Ethics, 172(2), 229–252. https://doi.org/10.1007/s10551-019-04215-7

Seele, P. (2017). Predictive sustainability control: A review assessing the potential to transfer big data-driven 'predictive policing' to corporate sustainability management. Journal of Cleaner Production, pp. 153, 673–686. https://doi.org/10.1016/j.jclepro.2016.10.175

Stergiou, C., Psannis, K. E., Gupta, B. B., & Ishibashi, Y. (2021). Security, privacy, and efficiency of sustainable cloud computing for big data and IoT. Sustainable Computing: Informatics and Systems, pp. 19, 174–184. https://doi.org/10.1016/j.suscom.2018.06.003

Stubbs, W., & Higgins, C. (2018). Stakeholders' perspectives on the role of regulatory reform in integrated reporting. Journal of Business Ethics, 147(3), 489–508. https://doi.org/10.1007/s10551-015-2954-0

Sustainability Accounting Standards Board (SASB). (2017). The state of disclosure: An analysis of the effectiveness of sustainability disclosure in SEC filings. https://www.sasb.org/knowledge-hub/state-of-disclosure-2017/

Thistlethwaite, J., & Mote, M. (2019). Business and the sustainability transition: Examining private sustainability regulation. Environmental Politics, 28(5), 844–863. https://doi.org/10.1080/09644016.2019.1626213

Venkataraman, R., & Brindha, G. (2021). Role of blockchain in supply chain transparency and traceability. Materials Today: Proceedings, 46, 7045-7049. https://doi.org/10.1016/j.matpr.2021.02.642

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Dirk Kok is a veteran data analytics expert with over two decades of experience in software architecture and data management, with a strong focus on the mining industry. As the co-founder of NxGN, he transforms complex data into actionable intelligence, driving operational excellence and strategic decision-making for mining operations.

With his extensive background as a software architect in mining, retail banking, capital markets, and IT security, Dirk brings a unique cross-industry perspective to data analytics challenges. His expertise lies in optimising data collection processes, integrating disparate sources, and employing advanced visualisation techniques to uncover valuable insights.

Dirk's approach combines rigorous analysis with a keen understanding of business objectives, enabling mining companies to enhance operational efficiencies, optimise resource allocation, and identify growth opportunities. His collaborative style ensures solutions are tailored to each organisation's needs, consistently delivering tangible business impact.

Passionate about the transformative power of data, Dirk is committed to helping mining executives navigate the digital landscape and leverage data as a strategic asset in an increasingly competitive global market.

Change impact evaluation dashboard for the adoption of modern mining technologies

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Change management is imperative for the adoption of new technologies, and the impact of changes needs to be understood and measured. This paper is based on a project funded by the Successful Application of Technologies Centred Around People (SATCAP) programme. The aim of this project was to verify a Change Management Blueprint for gold, zinc and platinum group metals (PGMs) and interlink it to a Change Impact Evaluation (IE) dashboard to determine impacts relating to the adoption of modern technology. Practical application testing was conducted on the adoption of a digital Shiftboss logbook at a PGM mine to validate and update the Change Management Blueprint. Co-creation workshops were held with various commodity operations to inform the development of the IE dashboard. The Change IE dashboard comprises organisational, technology, change adoption, people, and project indicators. The Change IE Dashboard has further been visually integrated into an environmental, social and governance (ESG) Impacts Lens Dashboard. The dashboards are available on the Mandela Mining Precinct website.

Keywords: Change Management, Critical Success Factors, Environmental, Social, and Governance, ESG, Modernisation

INTRODUCTION

As the South African mining industry modernises, appropriate change management becomes imperative for the adoption of new technologies. Additionally, the need to understand and measure the impact of changes has been identified. Increased modernisation is necessary to increase productivity, reduce costs, and improve occupational health and safety (Minerals Council South Africa, 2018; Singh, 2017). Modernisation may involve changes to people, processes, and technologies.

This project was funded by the Mandela Mining Precinct's Successful Application of Technologies Centred Around People (SATCAP) programme. SATCAP focuses on the impacts of mining modernisation on people in the minerals sector and lends support to the environmental, social, and governance (ESG) agenda. This paper is based on the project report (Botha *et al.*, 2024a) and related guideline (Botha *et al.*, 2024b).

This project is a continuation of work conducted in 2022 that focused on the development of a Change Management Blueprint for the mining industry for the adoption of modern technologies (Botha *et al.*, 2023). The Change Management Blueprint was based on Minerals Council South Africa's Mining Industry Occupational Safety and Health (MOSH) Leading Practice Adoption System (Malatji and Stewart, n.d.) and linked to Awareness, Desire, Knowledge, Ability and Reinforcement (ADKAR) principles (Prosci, n.d.).

The aim of the current project was to verify the 2022 tool and design a Change Impact Evaluation (IE) Dashboard to enable the determination of people-related change impacts in modern technology and systems adoption. The objectives of this project were to:

- Verify Change Management Blueprint; and
- Interlink the Change Management Blueprint to a Change IE Dashboard.

This project is linked to other work conducted in the SATCAP programme that has involved the development of a Socio-Economic Transformation IE Dashboard (Mahadeo *et al.*, 2024a), and Impact of Automation Dashboard (Mahadeo *et al.*, 2024b). The three dashboards have further been visually integrated into an ESG Impacts Lens Dashboard (Swettenham *et al.*, 2024).

REVIEW OF LITERATURE

This literature review focuses on change management approaches, success factors for the adoption of new technologies, and the previously developed Change Management Blueprint.

Technological developments have increased the need to investigate the appropriateness of change management practices (Ratana *et al.*, 2020). A review of change management models is provided in Table 1. Traditional top-down and stationary approaches to change management (e.g., Kurt Lewin's and Kübler-Ross's change models) are considered decreasingly relevant in current organisations (Ratana *et al.*, 2020; van Nistelrooij & van Nistelrooij, 2021). Akkaya *et al.*, (2021) and Fatsa & Akdaş (2023) argue that there is often a need to have a clear phased approach to change management. This need also entails having a clearly defined motivation or reason for the change (Okviana & Nurhaeni, 2020). Memon (2021) indicates that traditional models lack the focus on employee readiness to change. Models such as ADKAR (Prosci, n.d.) are seen to be more appropriate to current organisations due to the focus on employee engagement and readiness (Ali *et al.*, 2021).

Table I. Change Management Models

Model / Theory	Key Aspects	Sources Reviewed (Condensed List)
Kurt Lewin's 3-step change model	Three stages with subsets of activities under each. Employee involvement and constant communication. Approach is top-down hierarchical.	Burnes (2004, 2020 & 2021); Crosby (2020); Cummings *et al.*, (2016); Hussain *et al.*, (2018)
Dr John Kotter's 8-step process for leading change	Focus on identifying barriers to change. Initial top-down approach, however adjusted to departmental inclusion. Multi-step and phased with intricate roll-out.	Kotter (2007); Grenway (2021); Hughes (2022); Salman & Broten (2017)
Prosci's ADKAR change management model	Outcome-oriented. Inclusion of communication strategy. Increased stakeholder inclusion and minimisation of resistance to change.	Ali *et al.*, (2021); Gerdsri *et al.*, (2008); Kearns (2004); Prosci (n.d.)
The Kaizen change management model	Focused on continuous improvement through small ongoing positive changes. Has a production orientation. Collaborative approach and not hierarchical.	Carnerud *et al.*, (2018); Dang-Pham *et al.*, (2022); Garza-Reyes *et al.*, (2022)

Edward Deming's Plan-Do-Check (Study)-Act (PDCA) cycle	Continuous process with cyclical process. Problem-solving approach with feedback loops into change management.	Alauddin & Yamada (2019); Foulla (2021); Isniah *et al.*, (2020); Petrochenkov *et al.*, (2020)
McKinsey's 7-S model	Focused on organisational design. High dependence on change leaders within organisational structure. Identifies interdependence in structures.	Bellantuono *et al.*, (2021); Demir & Kocaoglu (2019); Errida & Lotfi (2021); Rosenbaum *et al.*, (2018)
Kübler-Ross change curve	Emphases on psychological / emotional factors of change. Has a leadership focus and not collaborative approach.	Cameron & Green (2019); Lukianov *et al.*, (2020); Orridge (2017); Nikula et al., (2010)

Various researchers have outlined the importance of understanding the impact of change processes on individuals, which in turn has an impact on other factors within the organisational structure (Akbar *et al.*, 2019; Cameron & Green, 2019; Griffin *et al.*, 2020). Akbar *et al.*, (2019) outlined the requirements of measuring change impact during technology implementation processes. As such, in addition to the review and alignment of change management models to the needs of current and future organisational practices, there is an identified need to understand and measure the impact of change (e.g., technology adoption projects) within organisations.

Numerous factors can hinder or facilitate the implementation of new technologies, and mixed successes have been reported in the South African mining industry (Pelders and Schutte, 2021). Examples of barriers to and facilitators of the successful implementation of new technologies are listed in Table II. Further success and failure factors for the adoption of new technologies in the South African mining sector identified in previous SATCAP research relate to job profiles, skills and training, health and safety, ergonomics, work systems, workplace culture, and implementation processes (Pelders *et al.*, 2019). A proposed modernisation adoption model for the South African mining industry, including key adoption factors, is shown in Figure 1.

Table II. Barriers and facilitators to the successful implementation of new technologies (Pelders and Schutte, 2021)

Barriers	**Facilitators**
• Premature application of technology • Initially high or unexpected costs • Employee attitudes or resistance to change • Fear of job loss as a result of the technology • Suspicion of management motives • Poorly engineered work systems • Technical failures • Poor ergonomics • Inadequate human-machine interface design • Inadequate training or skills • New health and safety risks created • Poor implementation, planning and control • Difficult mining conditions	• Optimal design of equipment • Human-system integration • Technology appropriate to work system • Technology maturity • Usability • Operator acceptance • Knowledge transfer • Training and support • Communication and coordination • Ownership of the technology or work system by the workforce • Worker involvement • Trust in the technology • Quantified benefits • Common vision

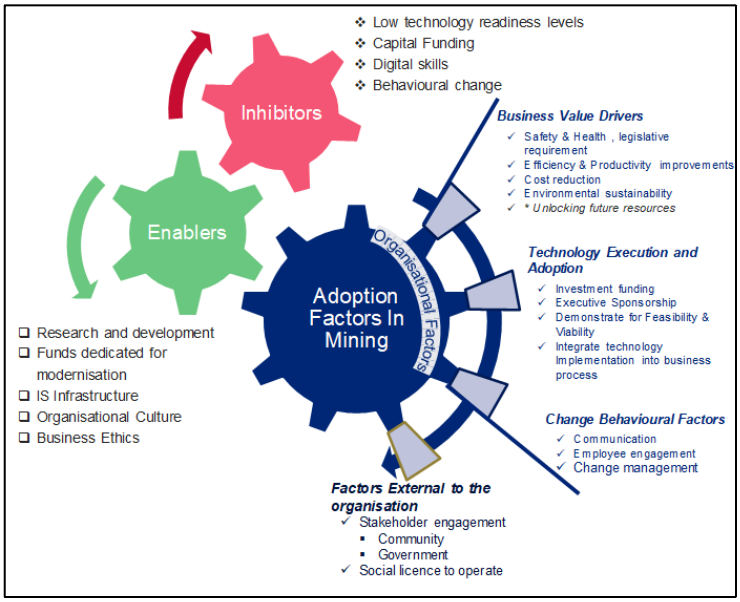

Figure 1. Proposed modernisation adoption model for the mining industry of South Africa (Ntsoelengoe, 2019).

In the project conducted for the design of the Change Management Blueprint, Botha *et al.* (2023), identified a number of considerations to be made prior to the implementation of the blueprint, including those relating to:

- Skills and training on technology
- Literacy levels
- IT infrastructure and systems
- Environmental considerations/working conditions
- Unions and Department of Mineral Resources and Energy stakeholder inclusion; and
- Unfeasibility of a one-size-fits-all approach.

The Change Management Blueprint incorporates the five phases of Prepare, Plan, Pilot, Roll-out and Support (3PRS), which each have sub-steps that need to be completed prior to moving to the next phase. Input into the process includes critical success factors, which are detailed later in this paper. The expected output is a successful change initiative with the impact highlighted on the Change IE Dashboard. The 3PRS Change Management Blueprint for the adoption of modern technologies in the mining industry, Microsoft Excel Tool, guideline, poster and How-To-Video may be accessed on the Mandela Mining Precinct website.

METHODS

Desktop research was conducted to identify indicators for change management relevant to technology adoption, and practices relating to dashboard design. Workshops were held with mining partner stakeholders to validate the Change Management Blueprint. The stakeholders included platinum group metal (PGM), gold and zinc operations. Practical application testing and validation involved user-acceptance assessment of a digital Shiftboss logbook at a modern PGM operation. The user-acceptance testing was also undertaken at gold and zinc operations in a preparation for future technology adoption projects. The design and development process for the dashboard reflected the Standford Design Thinking methodology. Co-creation workshops were held towards the development of the IE dashboard. An iterative approach was used for drafting the dashboard. Collaboration took place between the SATCAP work packages to create a unified ESG Impacts Lens Dashboard. User testing took place at mine sites, with final testing being undertaken at a PGM operation. Ethics approval for the project was received (EMS207/23).

Key questions that motivated the construction of indicators for the Change IE Dashboard design in respect to adoption of technology were:

- What is the impact of the adoption of new technologies on people?
- Where are people on the ADKAR spectrum to enable technologies' adoption?
- How ready is the organisation and people for adopting the new technology?
- What are the organisational impacts?

The research team included labour representatives, change managers, operational managers, and technical systems members during the various stakeholder sessions undertaken. There were a total of 15 focus group workshops, and seven validation sessions undertaken. The research team also undertook transfer sessions with information technology teams to ensure that the tools could be adopted into operations.

RESULTS AND DISCUSSION

Verification of the Change Management Blueprint

Practical application testing was conducted to validate and update the Change Management Blueprint. The case study focused on the adoption of a digital Shiftboss logbook at a modern PGM mine. The manual logbooks were to be replaced by digital versions, to enable real-time information and reporting. Key learnings during the verification process included those relating to technology readiness and functionality, contents on the device, the procedure, and change management considerations. Additionally, identified behavioural considerations included technological readiness, behavioural intention, performance expectancy, effort expectancy, optimism, innovativeness, discomfort, and insecurity.

The case study supported the inclusion of critical success factors (CSFs) for change management processes. CSFs are not a measurement of success, but rather the systems through which a company succeeds, which work in the 'background' of operations and projects at all times (Yarbrough, 2021). The CSFs are viewed as the input required to engage with people and commence with the identification of people-centred work to be done (Botha *et al.*, 2023). Three critical success factors to be addressed prior to the adoption of new technologies were identified during the development of the Change Management Blueprint (Botha *et al.*, 2023), and a fourth factor was identified through the verification process. The fourth factor related to modernisation and digitisation governance. There is the need to clearly identify the governance structures, including policies and procedures, that will dictate the adoption of the technology. The lack of governance structures has been noted to have a negative impact on the technology adoption process. Clear governance ensures that there is accountability taken for the adoption process and increases compliance and security. The CSFs are detailed in Table III.

Table III. Critical success factors for the adoption of new technologies

Critical success factor	Description	Industry validation	Summary of observations
Organisation digitisation journey / technology roadmap	When engaging with your team members, the digitisation roadmap can visually illustrate the journey and the aspects that should receive attention. During the process, the impact on people is acknowledged. Engage earlier rather than later.	• Contextual positioning • Reason for the change • Integration and target • Clarify the intent of the technology and process • Timeframe and transition period • Cost or incentive implications	• Understanding the digital transformation journey • Assisting to guide and manage change • Enhancing communication and collaboration
History assessment / lessons learnt	Opportunities should be created with current worksite to reflect on lessons learned with previous technology initiatives. It is also advisable to benchmark within the company where other or similar technologies were implemented.	• Leverage on stories • Reality check of blind spots • 'Bank' the lessons and sharing of ideas • Identify fear and mitigate the risk	• Learning from successes and failures • Personal narratives: Worker perspectives; leadership and decision-maker insights • Oral history and documentation
Current versus future resources (technology resources readiness)	Current resources and/or what is already in place for the current project.	• Confirmation of sponsorship and capacity/lack of capacity • Confirmation of enablement and credibility • Reduce uncertainty	• Resource planning as a pillar of change management: Cost efficiency, skills development, technology acquisition, and timely implementation • Reducing resistance and instilling hope: Transparency, inclusivity, and mitigation of risks
Modernisation and digitisation governance	Policies and procedural requirements and interface.	• Technology interface and accountabilities • Process of issuing • Process of servicing and accountabilities	• Accountability and transparency • Risk management • Efficient resource allocation • Effective decision making • Stakeholder engagement • Long-term sustainability • Compliance and legal considerations • Cybersecurity • Quality assurance

Change IE Dashboard

A Change IE Dashboard was developed to gauge impacts relating to change as a result of the adoption of new technologies. The Change Management Blueprint was foundational for the dashboard inputs. The Change IE Dashboard was developed using Power BI software. The data sources for the dashboard includes integration and links from the Change Management Blueprint and an Excel Blueprint. Screenshots of the Change IE Dashboard are shown in Figures 2 to 5. The Change IE Dashboard comprises sub-dashboards with 17 key indicators, as described in Table IV. The key indicators considered in the Change IE Dashboard relate to the following sub-dashboards:

- **Organisational:** aims to gauge how the technology projects are tracked in terms of impact on business processes, safety and financials.

- **Technology:** aims to gauge the level of readiness in adoption of new technology within the organisation, including leadership readiness, organisation readiness, technology readiness and policies, procedures and process readiness.
- **Change management process:** aims to assess the peoples' readiness in terms adoption of change and gauges awareness of new technology, desire for new technology, knowledge of new technology, ability to use new technology and support for new technology.
- **People:** aims to assess peoples' engagement with new technology and implementation thereof, and gauges the number of people using new technology, people using new technology versus baseline, proficiency in using new technology and peoples' satisfaction using new technology.
- **Project:** aims to gauge the level of each project implementation and success thereof in terms of planning and introduction of the new technology project in the mine environment, and measures whether the project was on time, within scope, of acceptable quality and within budget. Additionally, this group of indicators provides a summary of the success factors for successful adoption as per the Change Management Blueprint in terms of implementing the new technology and its adoption in the mines. It provides a measure of the CSFs in place to facilitate the successful adoption and assesses the level of accomplishment of the five phases for implementing the Change Management Blueprint (3PRS).

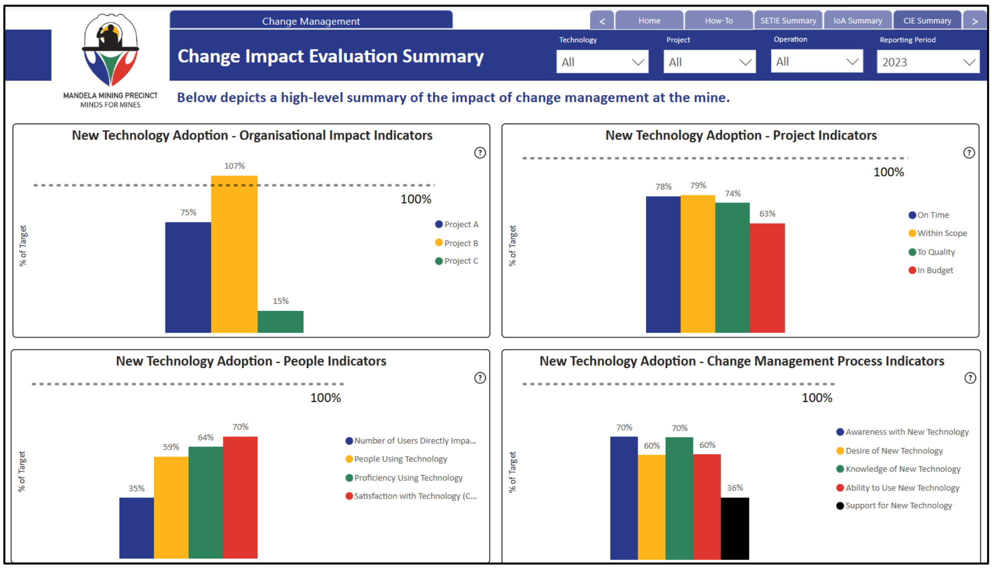

Figure 2. Change IE Dashboard – summary.

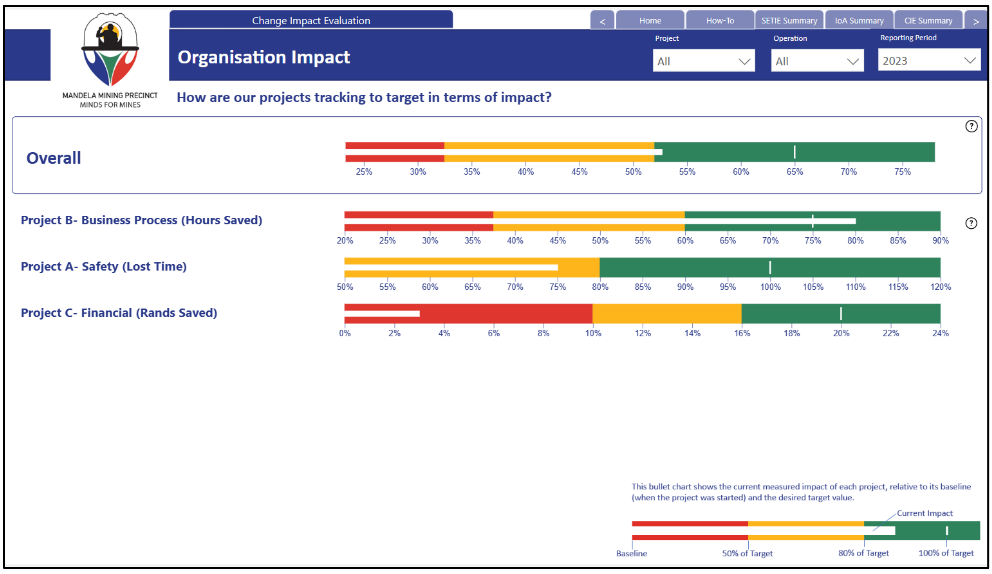

Figure 3. Change IE Dashboard – organisational impact.

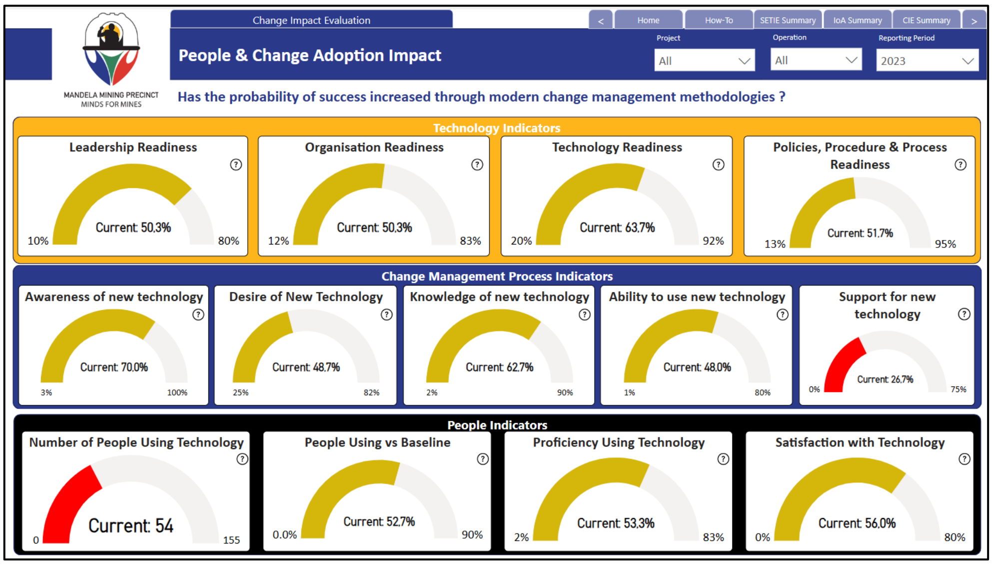

Figure 4. Change IE Dashboard – technology, process, and people impact.

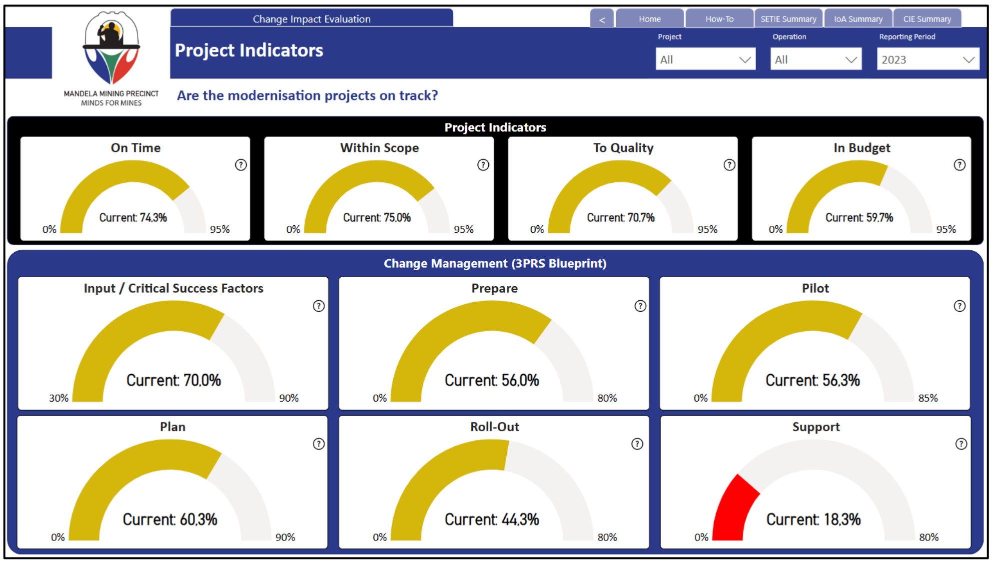

Figure 5. Change IE Dashboard – project indicator.

Table IV. Key indicators of Change IE Dashboard

People impact	
Number of people using the technology	This indicates the extent to which the technology is being applied across various levels of persons in the operation. It further indicates the intensity of focus areas in change management application.
People's proficiency in using technology	The determination can be made on how persons will cope with using the technology. It also outlines the need for level and intensity of training.
People's satisfaction with new technology	This indicator outlines the ease with which people will adopt the new technology. It was found that if persons have higher satisfaction of use, then there would be higher acceptance of the technology and therefore increase adoption probability.
Change adoption impact	
People's awareness of the new technology	The use of change management principles in the adoption process requires people to be made aware of the new technology. This increases the probability of success in the adoption process.
People's desire for the new technology	The positive desire of persons to utilise the technology has a direct link to the success of adoption
People's knowledge of the new technology	New technology adoption is often made difficult due to users not understanding the technology. The increase in knowledge lets users understand how the technology is applied and benefits their position.
People's ability to use the new technology	Users often resist the change taking place because they do not have the necessary ability to use the technology. The measurement of this indicator will also inform the training plan of the technology adoption project.
People's support for the new technology	The adoption process is made easier if users support the technology. It also has a more positive impact on fellow employees and the roll-out of technology in other sections of operations if users speak and interact positively around the technology.
Technology impact	
Leadership readiness for implementing the technology	This indicator outlines whether the leadership team for the adoption project has been successfully established. Further to this the indicator will highlight the level of understanding and support that is provided by leadership to the technology adoption project.
Organisational readiness for implementing the technology	This indicator illustrates the understanding that the organisation has of the technology. It also outlines the technology strategy and whether this is established within the organisational operating models.
Technology readiness for implementation	This is an indicator that is often overlooked, and the application of the Change Management Blueprint illustrated that there is a need for operations to determine

	the practical readiness (i.e., systems, current technology plug-in, support services, etc.,) for the technology project.
Organisational policies, procedures, and processes in place for implementation	There is a need for operations to have the necessary governance structures in place to have a higher probability of success. The measurement of these aspects will highlight to the implementing operation whether they have the necessary governance and procedural structures to manage the technology adoption process.
Organisational impact	
People results	This is the indicator that outlines the positive or negative impact that the change has had on the people within the organisation.
Internal business process results	This indicator will inform management whether there has been an improvement in the business processes after the adoption of the new technology.
Internal stakeholder results	Internal stakeholders have a strong driving force for the success of an adoption project. The measurement will indicate the impact that this has had on the internal stakeholders, such as the users and related parties.
Financial results	The measurement will highlight the impact there has been on the financial stance of operations after project implementation. It provides management with the necessary information to determine if the business case for the technology adoption has been successful and accurate.
Project indicators	
3PRS-Blueprint step progression	The indicator determines the progress of the Change Management Blueprint implementation/use during the technology adoption project. It ensures that change management principles have been incorporated during the technology adoption project.
Project management (time, cost, and scope)	This is an especially valuable indicator for management to determine the overall success of project implementation. These aspects within the indicator will clearly highlight whether the project has been managed within the basic parameters set.

ESG Impacts Lens Dashboard

The Change IE Dashboard is a sub-component of a visually integrated ESG Impacts Lens Dashboard, along with a Socio-Economic Transformation IE Dashboard, and Impact of Automation Dashboard (Figure 6). The ESG Impacts Lens Dashboard is an integrated platform that provides an overview of the impact of various factors during modernisation projects. It includes a Business Priorities Impacts summary, which represents data from the sub-dashboards relating to the internal workforce, external stakeholders, safety, cost, and production.

The operations that were involved in the development and verification of the ESG Impacts Lens Dashboard stated that while it addresses the needs of their operations, there may be some customisation required due to the different aspects of each project, different mining contexts, and as mining companies are in different phases of modernisation. The dashboard allows for this feature. The dashboard serves as a user-friendly, practical, and comprehensive platform to track the impacts of change for technology projects on mining operations.

The dashboards and related tools are available, along with a user-guidelines and supporting videos, on the Mandela Mining Precinct's website.

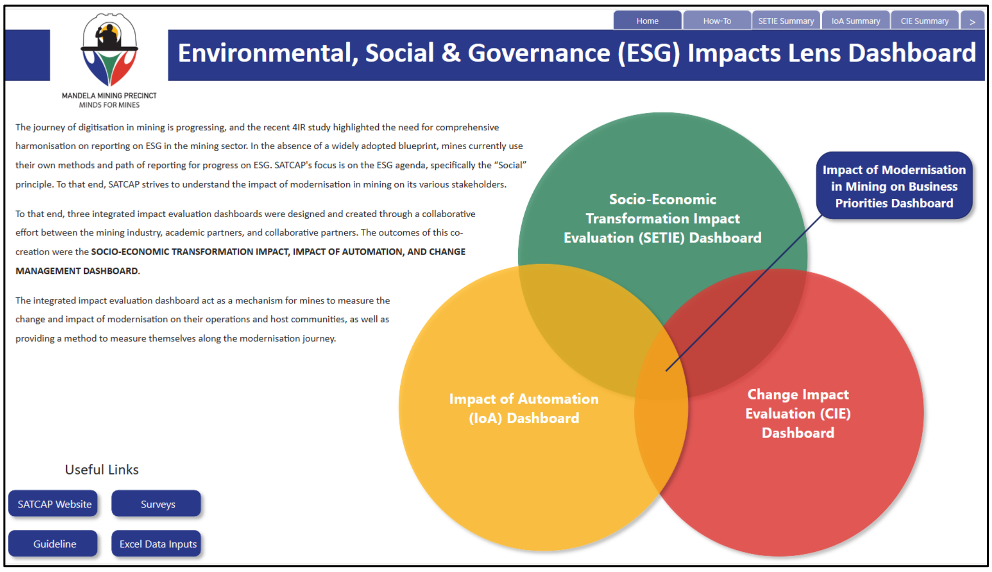

Figure 6. ESG Impacts Lens Dashboard landing page.

CONCLUSION AND RECOMMENDATIONS

In summary, as a result of literature review, stakeholder engagements and partner mine case studies, the Change IE Dashboard was developed. The Change Management Blueprint informed the key indicators for this dashboard. Four critical success factors were identified that need to be addressed prior to the application of change management for technology adoption. Implementation of the dashboard by the mining industry is intended to assist with improved understanding and evaluation of impacts associated with changes in technologies. The Change IE Dashboard integrates into the ESG Impacts Lens Dashboard, along with the Socio-Economic Transformation IE Dashboard and Impact of Automation Dashboard, and focuses on key business priorities of people, productivity, cost, and safety.

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REFERENCES

Akbar, M.A., Sang, J., Khan, A.A., Mahmood, S., Qadri, S.F., Hu, H. and Xiang, H., 2019. Success factors influencing requirements change management process in global software development. *Journal of Computer Languages*, *51*, pp.112-130.

Akkaya, B., Gunsel, A. and Yikilmaz, I., 2021. Digital Management Towards Society 5.0: A Review of the Framework for Kurt Lewin Theory During COVID-19 Pandemic. *Emerging Challenges, Solutions, and Best Practices for Digital Enterprise Transformation*, pp.120-137.

Alauddin, N. and Yamada, S., 2019. Overview of Deming criteria for total quality management conceptual framework design in education services. *Journal of Engineering and Science Research*, *3*(5), pp.12-20.

Ali, M.A., Zafar, U., Mahmood, A. and Nazim, M., 2021. The power of ADKAR change model in innovative technology acceptance under the moderating effect of culture and open innovation. *LogForum*, *17*(4).

Bellantuono, N., Nuzzi, A., Pontrandolfo, P. and Scozzi, B., 2021. Digital transformation models for the I4. 0 transition: Lessons from the change management literature. *Sustainability*, *13*(23), p.12941.

Botha, W.P., de Kock, N., Muller, R. and Ramparsad, S., 2023. Change management blueprint for the adoption of modern mining technologies. *Digital Transformation in Mining 2023.* The Southern African Institute of Mining and Metallurgy, pp.23 – 34.

Botha, W.P., Mahadeo, V., Pelders, J., Müller, R. and de Kock, N., 2024a. Change Management Blueprint (SATCAP 2022) Verified for Adoption of New Technologies; and Inter-Linked to a Change Impact Evaluation Dashboard. SATCAP WP 2.3. Milestone 3 – Final Report. Mandela Mining Precinct.

Botha, W.P., Müller, R., de Kock, N., Mahadeo, V., Pelders, J. and Ramparsad., S., 2024b. *Guideline: The Application of Change Management for the Adoption of Modern Mining Technologies.* SATCAP 2023: WP 2.3 – Skills. Mandela Mining Precinct.

Burnes, B., 2004. Kurt Lewin and the planned approach to change: a re-appraisal. *Journal of Management studies*, *41*(6), pp.977-1002.

Burnes, B., 2020. The origins of Lewin's three-step model of change. *The Journal of Applied Behavioral Science*, *56*(1), pp.32-59.

Burnes, B., 2021. Lewin, Kurt (1890–1947): The Practical Theorist. In *The Palgrave Handbook of Organizational Change Thinkers* (pp. 937-950). Cham: Springer International Publishing.

Cameron, E. and Green, M., 2019. *Making sense of change management: A complete guide to the models, tools and techniques of organizational change*. Kogan Page Publishers.

Carnerud, D., Jaca, C. and Bäckström, I., 2018. Kaizen and continuous improvement–trends and patterns over 30 years. *The TQM Journal*, *30*(4), pp.371-390.

Crosby, G., 2020. *Planned change: Why Kurt Lewin's social science is still best practice for business results, change management, and human progress*. CRC Press.

Cummings, S., Bridgman, T. and Brown, K.G., 2016. Unfreezing change as three steps: Rethinking Kurt Lewin's legacy for change management. *Human relations*, *69*(1), pp.33-60.

Dang-Pham, D., Hoang, A.P., Vo, D.T. and Kautz, K., 2022. Digital Kaizen: An Approach to Digital Transformation. *Australasian Journal of Information Systems*, *26*.

Demir, E. and Kocaoglu, B., 2019. The use of McKinsey's 7S framework as a strategic planning and economic assestment tool in the process of digital transformation. *Press Academia Procedia*, *9*(1), pp.114-119.

Errida, A. and Lotfi, B., 2021. The determinants of organizational change management success: Literature review and case study. *International Journal of Engineering Business Management*, *13*, p.18479790211016273.

Fatsa, N. And Akdaş, S., 2023. An Analysis of Post-Disaster Recovery Efforts in Turkey According to Kurt Lewin's Change Model Example of Kahramanmaraş and Hatay Provinces. *Assam Uluslararası Hakemli Dergi*, *10*(23), pp.43-56.

Foulla, B., 2021. Quality problem solving with PDCA cycle. *Management Research*, *5*(2), p.49.

Garza-Reyes, J.A., Christopoulos, C., Kumar, A., Luthra, S., González-Aleu, F., Kumar, V. and Villarreal, B., 2022. Deploying Kaizen events in the manufacturing industry: an investigation into managerial factors. *Production Planning & Control*, *33*(5), pp.427-449.

Gerdsri, N., Assakul, P. and Vatananan, R.S., 2008, July. Applying change management approach to guide the implementation of technology roadmapping (TRM). In *PICMET'08-2008 Portland International Conference on Management of Engineering & Technology* (pp. 2134-2140). IEEE.

Grenway, B., 2021. A Review and Application of John Kotter's" Leading Change". *Journal of Sociology and Christianity*, *11*(2), pp.91-95.

Griffin, R.W., Phillips, J.M. and Gully, S.M., 2020. *Organizational behavior: Managing people and organizations*. CENGAGE learning.

Hughes, M., 2022. Reflections: how studying organizational change lost its way. *Journal of Change Management*, *22*(1), pp.8-25.

Hussain, S.T., Lei, S., Akram, T., Haider, M.J., Hussain, S.H. and Ali, M., 2018. Kurt Lewin's change model: A critical review of the role of leadership and employee involvement in organizational change. *Journal of Innovation & Knowledge*, *3*(3), pp.123-127.

Isniah, S., Purba, H.H. and Debora, F., 2020. Plan do check action (PDCA) method: literature review and research issues. *Jurnal Sistem dan Manajemen Industri*, *4*(1), pp.72-81.

Kearns, B., 2004. Technology and change management. *School of Computing, Dublin Institute of Technology*.

Kotter, J.P., 2007. *Leading change: Why transformation efforts fail*. Harvard Business Review (Reprint).

Lukianov, D., Kolesnikova, K., Mezentseva, O. and Rudenko, V., 2020. The kübler-ross factor in managing the performance of technical and socio-economic systems. *Scientific Journal of Astana IT University*, pp.32-43.

Malatji, S. and Stewart, J.M., n.d. *The MOSH Leading Practice Adoption System: A Leading Practice in its Own Right.* The Chamber of Mines of South Africa. URL: https://www.mosh.co.za/ [Last Accessed 29 Jan. 2024].

Memon, F.A., 2021. Improving employee's engagement in change: Reassessing Kurt Lewin's model. *City University Research Journal*, *11*(1).

Minerals Council South Africa, 2018. *Modernisation: Towards the Mine of Tomorrow.* Fact sheet.

National Aeronautics and Space Administration (NASA), n.d. Technology Readiness Level Definitions. https://www.nasa.gov/wp-content/uploads/2017/12/458490main_trl_definitions.pdf. [Last accessed 28 January 2024].

Nikula, U., Jurvanen, C., Gotel, O. and Gause, D.C., 2010. Empirical validation of the Classic Change Curve on a software technology change project. *Information and Software Technology*, *52*(6), pp.680-696.

Okviana, L. and Nurhaeni, I.D.A., 2020, December. Management of the Educational Change in the Covid 19 Pandemic Era. In *6th International Conference on Social and Political Sciences (ICOSAPS 2020)* (pp. 184-188). Atlantis Press.

Orridge, M., 2017. *Change leadership: developing a change-adept organization*. Routledge.

Ntsoelengoe, J. S. (2019). *Factors Necessary for Effective Adoption of Modernisation in the South African Mining Industry.* Master of Business Administration. Gordon Institute of Business Science. University of Pretoria.

Pelders, J., Murambadoro, M. and Letsoalo, S., 2019. *Success and Failure Factors for the Adoption of the Intelligent Load Haul Dump (LHD).* Work Package 2.4-2.6. Successful Application of Technology Centred Around People (SATCAP). Mandela Mining Precinct.

Pelders, J. and Schutte, S., 2021. Worker inclusion in equipment development processes in the modernising minerals sector in South Africa. *The Journal of the Southern African Institute of Mining and Metallurgy, 121:* 63-69.

Petrochenkov, A.B., Gergel, N.A., Vshivkov, O.A. and Romodin, A.V. 2020. Developing a methodology for assessing technical and economic indicators for effective change management in the enterprise.

Prosci (n.d.). *The Prosci ADKAR Model.* https://www.prosci.com/methodology/adkar [Last accessed 29 Jan. 2024].

Ratana, S., Raksmey, C. and Danut, D., 2020. Conceptualizing a framework: A critical review of the development of change management theories. *Studies in Business and Economics*, *15*(2), pp.205-214.

Rosenbaum, D., More, E. and Steane, P., 2018. Planned organisational change management: Forward to the past? An exploratory literature review. *Journal of Organizational Change Management*, *31*(2), pp.286-303.

Salman, Y. and Broten, N., 2017. *An analysis of John P. Kotter's leading change*. Macat Library.

Singh, N. (2017). Weathering the 'perfect storm' facing the mining sector. *The Journal of the Southern African Institute of Mining and Metallurgy, 117:* 223-229.

Swettenham, T., Mahadeo, V., Sihlali, G., Govindasamy, K., Mavimbela, N., Botha, W.P., Pelders, J., Khan, S., Auret, M., Gruber, S., Osler, K., de Kock, N., Muller, R., 2024a. *ESG-Community Training-Needs, SMME Communication and Community Social-Needs Tools (SATCAP 2022) Verified and Inter-linked to an (ESG) Socio-Economic Transformation Impact Evaluation Dashboard.* Milestone 3 – Final Report. SATCAP WP 2.1.

Swettenham, T., Mahadeo, V., Sihlali, G., Govindasamy, K., Mavimbela, N., Botha, W.P., Pelders, J., Khan, S., Auret, M., Gruber, S., Osler, K., de Kock, N., Muller, R., 2024b. *Verification of the Digital Leadership Competencies Gap Assessment Tool (SATCAP 2022) and Interlinked to an Automation Impact Evaluation (IE) Dashboard.* Milestone 3 – Final Report. SATCAP WP 2.2.

Swettenham, T., Mahadeo, V.J., Sihlali, G.L., Govindasamy, K.K., Mavimbela, N.Z., Gruber, S., Osler, K., Botha, W.P., Pelders, J., Khan, S. and Ramparsad, S., 2024. *User Guideline for the ESG Impacts Lens Dashboard: An Integration of Socio-Economic Transformation, Automation and Change Impact Dashboards.* SATCAP 2023: WP 2.1, 2.2 and 2.3 – Skills. Guideline. Mandela Mining Precinct.

van Nistelrooij, A. and van Nistelrooij, A., 2021. Organisation Development: As Coupled to the Original Work of Kurt Lewin. *Embracing Organisational Development and Change: An Interdisciplinary Approach Based on Social Constructionism, Systems Thinking, and Complexity Science*, pp.87-128.

Yarbrough, Q., 2021. *What is a Critical Success Factor?* Available at: https://www.projectmanager.com/blog/critical-success-factor [Last accessed: 08 Feb. 2024].

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The cost of carbon neutrality: A weighted average cost of energy approach

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Achieving carbon neutrality is a priority for many companies striving to align with global sustainability goals. However, the economic challenge of transitioning from traditional fossil fuels to renewable energy sources remains significant. This paper explores a strategic methodology to manage and minimise the financial burden of this transition, specifically focused on the mining industry in South Africa. By leveraging the concept of a weighted average cost of energy (WACE), the paper argues for an optimised energy mix that balances the costs of individual renewable energy interventions, high and low, against the overarching goal of reducing overall energy expenses. Drawing parallels with the Pareto principle, the paper emphasises the importance of targeting 'quick wins' (renewable energy solutions that are both cost-effective and impactful) before addressing the more challenging and expensive aspects of energy replacement. The analysis highlights how focusing on these initial, high-impact interventions can significantly lower the WACE, making the journey to carbon neutrality more financially viable. The final segments of energy replacement, characterised by their high costs and implementation difficulties, are approached with a nuanced strategy, acknowledging their necessity while optimising their cost impact through a diversified and balanced energy portfolio. Through this weighted average cost framework, companies can achieve a lower overall cost of energy while progressing towards carbon neutrality. The paper presents a fictitious case study, based on a real mining operation, to develop strategic recommendations to illustrate the feasibility and benefits of this approach, ultimately contributing to more sustainable and economically sound energy transition strategies for mining companies.

BACKGROUND AND CONTEXT

Global efforts to achieve carbon neutrality have intensified in response to climate change. The shift from fossil fuels to renewable energy sources is essential to reduce greenhouse gas (GHG) emissions. However, the economic implications of this transition pose significant challenges for businesses aiming to maintain viability while contributing to environmental goals.

Many companies worldwide have committed to reducing their GHG emissions in a pledge to contribute towards achieving the goals set out by the Paris Accord. For example, large mining companies such as Anglo American have committed to achieving a 30% reduction in Scope 1 and 2 emissions by 2030, and net-zero by 2040 (Anglo American, 2023). Similarly, BHP has committed to achieving Scope 1 and 2 carbon neutrality by 2050 (BHP, 2024). Achieving carbon neutrality is not solely an environmental target; it is also an economic challenge. Companies face the dual task of adjusting their operational frameworks to sustainable models while managing costs to remain competitive.

These targets, however ambitious, still rely heavily on the company’s willingness to implement the interventions which will result in the emissions mitigations necessary, and ultimately will boil down to economic viability of implementation. In many cases low-carbon alternatives are not considered unless they are equal to or cheaper than current fossil fuel energy sources.

This approach may be suitable in the short term to implement quick-win interventions (e.g., 2030 targets), but in the long run will prove to be unreasonable as the interventions target harder-to-reach areas of energy consumption.

Objective of the Paper

The primary objective of this paper is to present the weighted average cost of energy (WACE) as a strategic and financially viable framework to facilitate the transition towards carbon neutrality in the mining industry. By leveraging the WACE methodology, this paper aims to guide high-level decision-makers in prioritising and integrating multiple GHG mitigation projects, each with distinct business cases, into a cohesive strategy that achieves an overall reduction in the cost of energy. This approach enables companies to balance short-term cost efficiency with long-term sustainability goals, while also demonstrating how the adoption of diverse renewable energy interventions, including those with initially higher costs, can collectively result in significant financial and environmental benefits. Through a case study, this paper illustrates the practical application of the WACE framework and provides strategic recommendations for optimising energy portfolios in support of carbon neutrality.

FUNDAMENTAL CONCEPTS

The Energy Trilemma

The energy trilemma, for the context of this paper, refers to the trade-off that all sources of renewable energy face with respect to affordability, sustainability and security. The trilemma is similar to the well-known project management concept of cost, quality and time, in which it is well accepted that you cannot have all three criteria met fully. For example, if you want something of high quality and completed in a short period of time, you have to be willing to pay a premium to achieve this. With renewable energy sources, the trade-off is much the same except that instead of quality you have sustainability, and instead of time you have security of supply (Githinji, 2021).

The energy trilemma is best described through an example comparing a traditional fossil fuel energy source, coal fired power, and a renewable energy source, grid-connected solar photovoltaic (PV). The coal fired power is both cheap and reliable but its major trade-off is that it is far from sustainable. The grid-connected solar PV on the other hand is both sustainable and (in recent years) highly affordable, but its major drawback is that it is highly susceptible to climatic changes and even in the best conditions achieves a 25 to 30% capacity factor.

Figure 1. Energy trilemma (Source: Climate Emergency JSY).

Understanding the energy trilemma is critical when considering strategic planning to achieve carbon neutrality in that it clearly demonstrates that to achieve the high-levels of sustainability, while maintaining a high-degree of energy security from renewable sources, companies will have to make allowances for an increased cost in energy for some energy sources.

GHG Emissions Mitigation Hierarchy
The mitigation hierarchy provides a structured framework for addressing GHG emissions and climate change. It outlines a series of steps that guide organisations in prioritising actions to minimise their environmental footprint effectively (HOLCIM, n.d.).

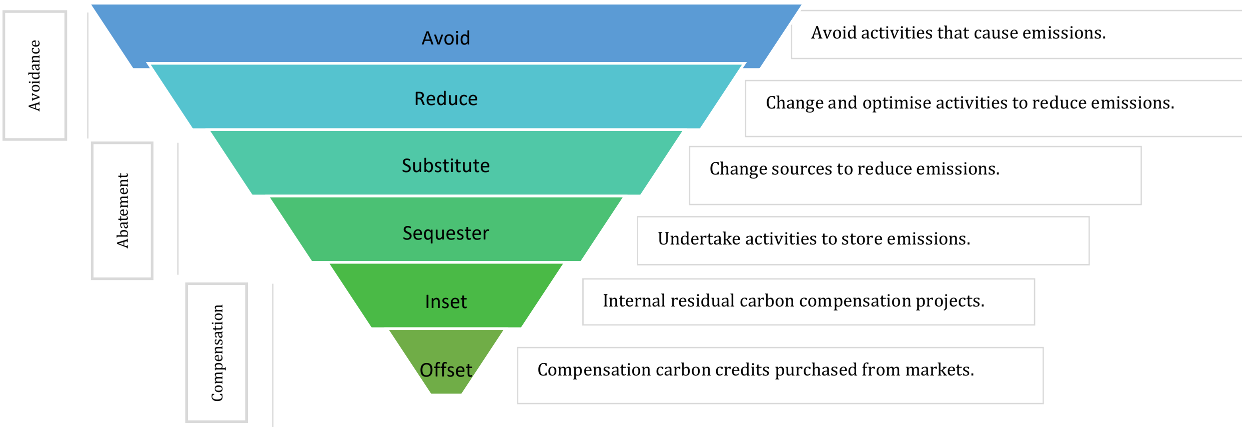

Figure 2. GHG mitigation hierarchy.

1.1. Pareto Principle
The Pareto principle, often referred to as the 80/20 rule, suggests that 80% of effects come from 20% of causes. Another way to consider the 80/20 rule is that 80% of the results can be achieved through implementation of 20% of the potential solutions. When applied to the implementation of carbon mitigation projects, this principle can be a powerful tool for prioritising actions that yield the greatest environmental benefits with the least expenditure of resources. The Pareto principle is an important concept to remember when developing strategies to achieve carbon neutrality, as it emphasises the importance of prioritising high-impact projects in the short term. However, achieving comprehensive carbon neutrality also demands attention to less impactful areas after the 'quick wins' have been secured, ensuring a holistic approach to achieving emission reduction goals (Miller, 2020).

Weighted Average Cost of Energy
The weighted average cost of energy is a mathematical method to determine the single cost per unit of energy across multiple energy sources; across an entire organisation or operation. The method requires all energy source consumptions and costs to be represented in a common unit, typically USD (or other currency) and gigajoules or megawatt-hour (GJ, MWh, 1GJ = 0.278 MWh).

$$Weighted\ Average\ Cost\ of\ Energy = \frac{EC_A * COE_A + EC_B * COE_B + EC_C * COE_C \dots}{EC_A + EC_B + EC_C \dots}$$

$where:$
$EC_{A,B,C\dots} = energy\ consumption\ of\ source\ A, B, C$
$COE_{A,B,C\dots} = average\ cost\ per\ unit\ of\ energy\ of\ source\ A, B, C$

METHODOLOGY

Framework Introduction
The WACE framework firstly works to determine a prioritised list of implementable carbon mitigation options. It then calculates the cost impacts of the various GHG mitigation options, weighted by their consumption ratios to determine the net effect of the combined implementation. This method presents an approach to implement GHG mitigation projects and aims to provide a clearer picture of financial impacts across different energy mix scenarios, and an overall view of the net cost of energy before and after implementation of a portfolio of mitigation projects.

The WACE Framework
Step 1: Understanding the Current and Projected Energy Mix and Cost
The first step is to determine the current and projected baseline (without intervention, sometimes referred to 'Business as Usual' or "Do-nothing' scenario) energy mix is, and the current and projected baseline WACE. Typically, this is done at a single site level and then 'rolled up' to give a picture of the overall outlook for energy costs into the future. It is important at this stage to incorporate influencing factors such as:

- **Current and future production capacities:** An increase or decrease in production capacities can influence energy consumption rates. For example, higher throughput through a mill circuit will result in a higher energy consumption relative to the baseline year.
- **Expected changes in specific energy consumption:** An increase or decrease in energy consumption as a result of lower or higher capacities or a changing production environment can change energy consumption relative to the baseline year; e.g., deep level mining activities can see an increase in energy consumption per tonne mined as the mining extends deeper underground.
- **Future energy unit costs:** Different energy sources have different future price escalation estimates.

At this point, the relative weights (in terms of both consumption and cost) of each energy source can be calculated. The result of the process is shown in Tables I and II.

Table I. Example of As-is energy mix

Energy Source	**Annual Energy Consumption (GJ)**	**Annual Cost (USD)**	**Annual Emissions (tCO2e)**	**As-is Average Cost of Energy (USD/GJ)**	**As-is Emissions Factor (tCO2e/GJ)**	**% of Energy Mix (Relative Weight)**	**% Cost of Energy Mix**	**% Emissions**
Electricity								
Diesel								
Thermal Coal								
…								

Table II. Example of business as usual energy mix projection

Energy Source	**As-is**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**…**	**Year N**
Electricity							
Diesel							
Thermal Coal							
…							
Total Energy							
WACE							

Step 2: Scope Individual Mitigation Options
Now that the current and future energy mix – relative consumption ratios and current weighted average cost of energy – is understood, scoping of potential mitigation options to replace the current energy mix can be done. The WACE framework does not propose a specific set of mitigation measures, nor make any recommendations on which exact measures to implement, but rather highlights important information which should be gathered for each potential measure.

Important information to gather for each potential mitigation option includes:

- **Energy Output (Capacity & Generation Potential)**
  - Installed capacity (MW or GW) and estimated annual energy generation (MWh)
- **GHG Emission Reduction Potential**
  - Estimated reduction in CO_2e (CO_2 equivalent) emissions compared to current energy source
- **Cost Metrics**
  - Capital expenditure for installation or setup
  - Operating expenditure including maintenance and fuel costs (if applicable)
  - Levelised cost of energy in $/MWh or equivalent
  - Payback period and return on investment
- **Resource Availability**
  - Availability and consistency of energy supply (e.g., intermittency of renewables like solar and wind)
  - Local availability of resources (e.g., sunlight, wind, water, biomass)
- **Technological Maturity and Reliability**
  - Technology readiness level and proven track record in similar projects or environments
  - Operational lifespan and reliability metrics (e.g., downtime, failure rate)
- **Integration with Existing Infrastructure**
  - Compatibility with the existing energy grid or systems
  - Infrastructure development needs (e.g., transmission lines, storage solutions)
- **Regulatory and Policy Incentives**
  - Availability of government subsidies or tax incentives
  - Future regulatory risks (e.g., carbon pricing, emissions trading schemes)
- **Environmental and Social Impact**
  - Impact on local ecosystems and biodiversity
  - Water usage and land footprint (especially for renewables like solar farms, hydro, and biomass)
  - Social acceptance and potential impact on local communities
- **Scalability and Flexibility**
  - Ability to scale the technology to meet future energy demand
  - Flexibility in operation (e.g., ease of expanding or reducing capacity)
- **Resilience and Climate Adaptation**
  - Resilience to extreme weather events and climate change impacts
  - Adaptability of the technology to changing environmental conditions
- **Supply Chain and Resource Security**
  - Availability of critical materials and components (e.g., rare earth metals for batteries)
  - Risk of supply chain disruptions
  - Recycling and disposal options for end-of-life equipment

The outcome of this step is a comprehensive list of potential mitigation options for each current energy source along with the necessary metrics necessary to prioritise implementation.

Step 3: Prioritise Implementation
When implementing alternative energy sources as part of a carbon mitigation strategy, a structured approach to prioritisation is essential to ensure that both environmental goals and financial constraints are balanced effectively. While many prioritisation methodologies exist, the process can be arduous and

there is no single method to ensure correct prioritisation. The WACE methodology primarily focuses on two key prioritisation frameworks: the GHG mitigation hierarchy and the Pareto principle. Additionally, for more nuanced decision-making, the analytical hierarchical process (AHP) (Saaty, 1980) can provide a systematic method to rank potential mitigation options.

The following steps can be followed to prioritise the implementation of the scoped mitigation measures:

1. **Initial Screening Using GHG Mitigation Hierarchy**: Begin by identifying the full range of potential interventions and apply the hierarchy to filter out less impactful or costly measures, focusing on avoid, reduce, and replace strategies.
2. **Pareto Principle Application**: Within the selected interventions, identify the 20% of actions that can achieve 80% of emissions reductions, ensuring a focus on high-impact, low-cost options.
3. **(Optional) AHP for Detailed Ranking**: Use AHP to rank the remaining measures, considering multiple factors such as technical feasibility, regulatory requirements, community acceptance, and financial return on investment.
4. **Implementation Roadmap**: Develop an implementation roadmap that aligns with available resources, ensuring that quick wins are addressed first, while long-term projects that may be more costly or complex are phased in over time.

The outcome of this step is a prioritised list of scope mitigation options with an indication of an implementation timeline as per Table III.

Table III. Example of prioritised GHG mitigation options

Mitigation Option	**Target Energy Source**	**Implementation Horizon**	**Average Cost of Energy**
Solar PV Project A	Grid Electricity	Y2	
Biofuel Project A	Diesel	Y5	
…			

Step 3: Integration
The final step in the framework integrates the baseline scenario with the scoped mitigation options to determine the net effect on the projected cost of energy across an entire organisation. The outcome of this step, similar to the outcome of step 1, is a table projecting the new energy mix (now appended with new energy sources) and costs into the future (referred to as 'to-be' scenario).

Table IV. Example 'to-be' energy mix projection

Energy Source	Relative Weight	As-is	Year 1	Year 2	Year 3	Year 4	…	Year N
Electricity								
Diesel								
Thermal Coal								
Solar PV Project A								
Biofuel Project A								
…								
WACE (as-is)								
WACE (to-be)								

As the above table is populated with potential mitigation options, it should become clear that initially the WACE across the energy mix will decrease substantially in the short-term. These short-term gains will allow the long-term mitigation options (which are expected to have an increased cost of energy individually) to be implemented without increasing the overall weighted cost of energy by the same degree, ideally remaining below the as-is baseline scenario.

CASE STUDY

The following case study is an illustrative example and briefly summarises the outcomes of the application of the WACE methodology at a large industrial entity. It is important to note that the case study is presented purely to demonstrate the application of the WACE methodology and not to suggest that the mitigation options included formed part of an actual implementation strategy.

Step 1: Understanding the Current and Projected Energy Mix and Cost
The entity used for the case study consists of multiple operations which include open-cast and deep level mines, concentrator plants, as well as smelting and refining operations. The entity's energy mix consists primarily of electricity, coal and diesel.

Table V. Case study As-is energy mix

Energy Source	Annual Energy Consumption (mil GJ)	Annual Cost (mil USD)	Annual Emissions (mil tCO2e)	As-is Average Cost of Energy (USD/GJ)	As-is Emissions Factor (tCO2e/GJ)	% of Energy Mix (Relative Weight)	% Cost of Energy Mix	% Emissions
Grid Electricity	13.73	204.33	3.66	14.88	0.267	67%	61%	87%
Coal (Thermal + Coke)	3.50	30.64	0.33	8.75	0.095	17%	9%	8%
Diesel	2.80	86.96	0.21	31.06	0.074	14%	26%	5%
Petrol	0.00	0.11	0.00	33.46	0.069	0%	0%	0%

LPG	0.30	11.34	0.00	37.81	0.006	1%	3%	0%
Paraffin	0.01	0.26	0.00	26.18	0.071	0%	0%	0%

The entity currently projects an increase in production of ~1% per year for the next 10-20 years. Considering the increase in production, the projected energy mix uses the as-is specific energy consumption ratio (unit of energy consumed per unit of production) as the basis for calculating the projected energy consumption. There are no major changes in the mode of production and therefore no change to specific energy consumption projected for the next 10-20 years.

Table VI. Case study projected as-is energy mix (business as usual)

Energy Source	As-is	Y1	Y2	Y3	Y4	Y5	Y6	Y7
Grid Electricity	13.73	13.79	13.79	13.83	13.92	13.93	13.94	14.07
Coal (Thermal + Coke)	3.50	3.52	3.52	3.53	3.55	3.56	3.56	3.59
Diesel	2.80	2.81	2.82	2.82	2.84	2.84	2.85	2.87
Petrol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPG	0.30	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Paraffin	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Energy Use (mil GJ)	**20.36**	**20.44**	**20.44**	**20.50**	**20.64**	**20.65**	**20.67**	**20.86**
WACE (USD/GJ)	**14.08**	**14.08**	**14.08**	**14.08**	**14.08**	**14.08**	**14.08**	**14.08**

For the purposes of the case study, energy cost inflation is not considered and therefore the projected WACE remains USD 14.08/GJ.

Step 2+3: Scope Mitigation Options and Prioritise Implementation
Table VII contains the prioritised list of scoped mitigation options which were listed for the case study. It is important to note that priority was given based on a number of factors including the implementation timeline, strategic alignment with company goals, energy cost, potential impact, capital requirements, etc.

Table VII. Case study prioritised GHG mitigation options

Priority	Mitigation Option	Target Energy Source	Implementation Horizon	Average Cost of Energy (USD/GJ)
1	Renewable Electricity (Wind + Solar)	Grid Electricity	Y1	7.22
2	Renewable Natural Gas	Coal	Y3	7.24
3	Hydrogen	Diesel (Large Capacity)	Y2-Y5	23.95
4	Synthetic Diesel	Diesel (Small Capacity)	Y4	47.55
5	Renewable Natural Gas	LPG	Y4	7.24
6	Synthetic Paraffin	Paraffin	Y4	47.55

The scoped projects demonstrate that the priority project – renewable electricity from wind and solar to replace grid electricity – produces a significantly lower cost of energy compared to the 'as-is' scenario. The lower priority projects, however, have a longer implementation horizon and all have a significantly higher cost of energy in comparison to the 'as-is' scenario.

Step 3: Integration

Figure 3 shows the result of integrating the scoped priority projects into the projected energy mix profile for the entity. The implementation of all scoped priority projects was done progressively with the aim of full implementation by 2034 (Y15).

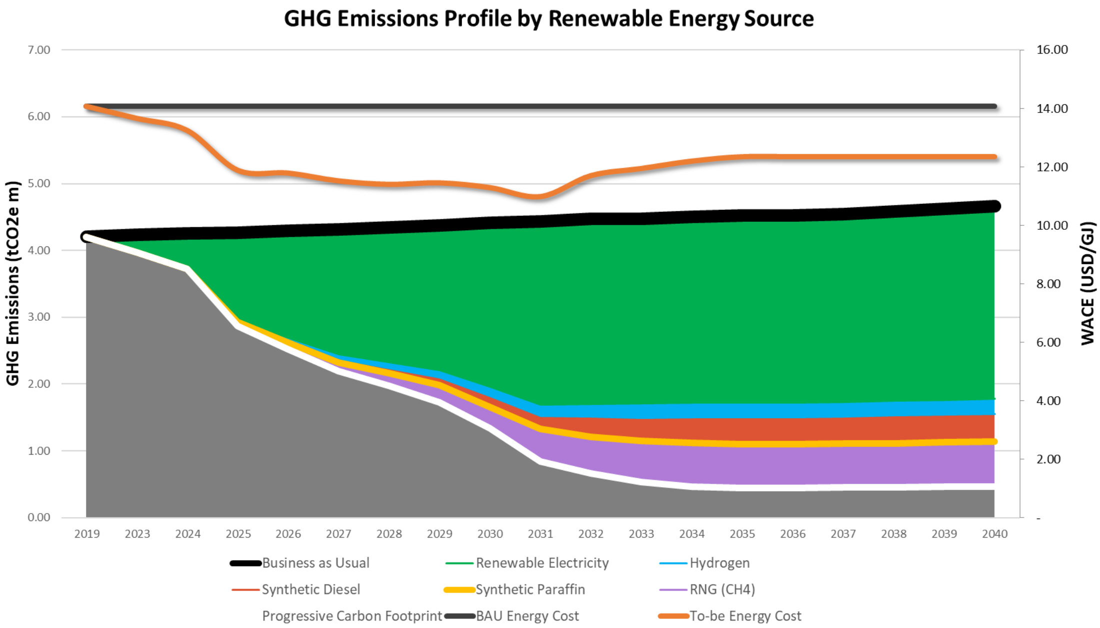

Figure 3. Case study integrated WACE methodology outcome.

DISCUSSION

The implementation of the WACE methodology demonstrates that deploying multiple GHG mitigation projects, including some that might not have been initially selected due to their higher energy costs compared to the existing 'as-is' scenario, can ultimately result in an overall lower cost of energy. By considering the collective impact of various renewable energy and carbon reduction initiatives, the WACE approach highlights how the integration of diverse technologies and strategies can lead to a more cost-efficient energy solution, while also advancing carbon neutrality goals.

INTERPRETATION OF FINDINGS

Advantages of the WACE Approach

- The goal of the WACE method is to chart a path to carbon neutrality through a variety of measures by considering the overall cost of energy across the interventions.
- The framework allows companies to focus on 'quick wins' that have the highest return in terms of both cost savings and GHG reductions, ensuring immediate progress.
- The phased implementation provides flexibility to adapt to changing energy demands, regulatory environments, and technological advancements.
- It promotes a balance between financial imperatives and environmental goals, ensuring that GHG mitigation measures are sustainable both economically and operationally.

CONCLUSION

The application of the WACE framework in the context of carbon neutrality demonstrates a viable and economically sound approach to achieving GHG reduction goals within energy-intensive industries like mining. The methodology shows that by implementing a combination of renewable energy projects – some of which may initially appear cost-prohibitive –companies can collectively reduce their overall energy costs. By initially prioritising cost-effective, high-impact projects and progressively incorporating more challenging interventions, companies can mitigate their carbon footprint without compromising on financial viability.

The WACE framework supports decision-makers in optimising energy portfolios, balancing short-term financial pressures with long-term sustainability goals. Importantly, this approach emphasises the value of creating a diversified energy mix, which includes renewable energy interventions that, while costly in isolation, collectively contribute to a lower overall cost of energy and drive progress toward carbon neutrality.

FINAL THOUGHTS

The WACE methodology provides a robust framework for companies in energy-intensive sectors to transition toward carbon neutrality in a cost-effective and structured manner. By strategically managing a portfolio of energy projects, the framework helps mitigate financial risks while aligning with long-term sustainability goals. The success of this approach lies in its flexibility, allowing for an adaptive energy mix that evolves with technological advances, regulatory changes, and market conditions.

REFERENCES

Anglo American. (2023). *Climate Change: Towards a low carbon future*. Retrieved from Anglo American: https://www.angloamerican.com/sustainable-mining-plan/healthy-environment/climate-change

BHP. (2024). *Climate Transition Action Plan 2024.*

Climate Emergency JSY. (n.d.). *Carbon Neutral Roadmap: Preferred Strategy Report.*

Githinji, E. (2021, August 6). *Understanding the Energy Trilemma*. Retrieved from Clean Energy 4 Africa: https://cleanenergy4africa.org/understanding-energy-trilemma/

HOLCIM. (n.d.). *Biodivesity- Measuring positive biodiversity impact*. Retrieved from https://www.holcim.com/sustainability/nature/biodiversity

Miller, R. (2020). *Can We Address Emissions Using The Pareto Principal?* Retrieved from Energy Central: https://energycentral.com/c/pip/can-we-address-emissions-using-pareto-principal

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation.* McGraw-Hill.

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James has hands-on experience in the development of energy management and diversified energy mix strategies, as well as guidelines for implementation of related projects, for major mining companies in South Africa. As a founder and director of Carbon Neutral Energy Systems (C-NES), James' goal for the South African mining industry is to see the long-term implementation of renewable energy mix which balances short term results and long-term sustainability.

Road to carbon neutrality – opportunities, innovations, and strategic implications for the mining industry

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The South African economy is fundamentally linked to its rich mineral resources, creating a complex relationship known as the minerals-energy complex. While this sector is crucial for both domestic and global markets, it is confronted by multifaceted challenges such as declining productivity, increasing operational costs, fluctuating commodity prices, and the urgent need to address environmental concerns and achieve carbon neutrality. As the world races to limit global warming to 1.5°C, as discussed in the Paris Agreement's mandate and sustainable development goals, the mining sector faces increasing pressure to reduce its carbon footprint and transition towards carbon neutrality. This industry is critical in providing raw materials needed for low-carbon energy transition, yet it also contributes significantly to greenhouse gas emissions. Transitioning to carbon neutrality ensures a sustainable supply of these materials while reducing the industry's energy consumption and environmental impact. Carbon neutrality in the mining industry is essential for mitigating climate change and addressing energy security and sustainability while improving air quality and ecological recovery. Achieving carbon neutrality drives innovation and investment in green technologies, enhances reputation and stakeholder trust, and supports a just transition to a low-carbon economy. Exploring the concept of carbon neutrality and its importance for the mining industry, particularly in South Africa, involves examining the strategic implications for mining companies, including the challenges and opportunities they face on the road towards carbon neutrality. Against this backdrop, this paper outlines the various factors which will play a pivotal role in carbon neutrality of the mining industry, necessitating a dual focus on resource provision and internal decarbonisation.

Keywords: carbon neutrality, mining industry, environmental sustainability, green technologies, strategic implications.

INTRODUCTION

South Africa's economy is heavily reliant on its mineral resources, with mining contributing significantly to its gross domestic product (GDP) and employment. In 2015, mining accounted for approximately 7.1% of South Africa's GDP, contributing R286 billion and employing nearly half a million people, representing about 3% of total employment (Moorosi & Vusi, 2021). The minerals-energy complex (MEC) is a critical framework that illustrates the country's mining, energy production, and industrial development interconnectedness. It encompasses the relationship between mining, energy-intensive mineral processing, and coal-to-electricity sectors, which evolved together due to abundant coal resources. This relationship has evolved significantly, particularly in the context of global climate change pressures and environmental, social and governance (ESG) requirements. The MEC complex is vital for understanding South Africa's industrial growth and energy supply. However, it faces challenges due to its heavy reliance on coal, which is increasingly scrutinised for its environmental impact and market volatility (Lucy, 2015); (Ting, 2015).

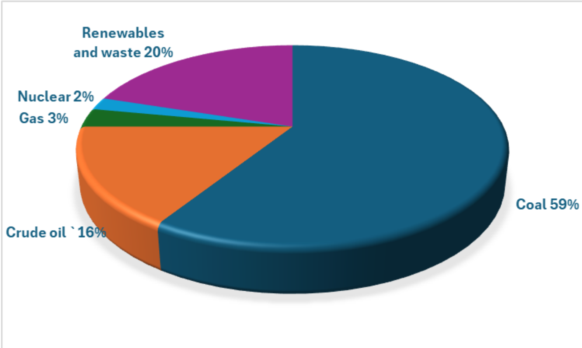

Figure 1. South Africa's Energy Mix (Barahira, Okudoh, & Eloka-Eboka, 2021).

The mining industry is responsible for a substantial portion of global greenhouse gas (GHG) emissions. The gold mining sector alone emits over 100 Mt CO_2-e annually, with emissions intensity varying widely by country; from 129 to 2754 kg CO_2-e/oz (Ulrich, *et al.*, 2022). Major mining nations like China, the USA, and India exhibit high emissions, with China leading at 195.47 Mt (Sajid, 2019). As nations strive for carbon neutrality, the sector's alignment with the Paris Agreement and the Sustainable Development Goals (SDGs) becomes increasingly vital. In China, the metal mining sector is under pressure to peak carbon emissions by 2030 and achieve carbon neutrality by 2050, highlighting the urgency of technological advancements in emissions reduction (Guo, *et al.*, 2022). Transitioning to cleaner energy sources and enhancing energy efficiency is critical for reducing emissions, with potential reductions of up to about 46% from energy substitution (Ulrich, *et al.*, 2022). The mining industry is also positioned to benefit from a global carbon tax, as it could drive demand for minerals essential for renewable energy technologies (Cox, *et al.*, 2022).

The Paris Agreement emphasises the need for countries to commit to reducing emissions, which directly influences mining policies and practices. Effective mineral policies in the European Union have shown that sustainable practices can lead to increased production while simultaneously reducing CO_2 emissions by over 20% (Janikowska & Kulczycka, 2021). The mining sector is making strides to address SDGs, particularly those related to health, poverty reduction, economic growth and environmental goals (Papafloratos, 2023). Strategic integration of environmental considerations is essential for achieving carbon neutrality and sustainable competitiveness in mining (Wei, 2024).

The regulatory landscape for carbon neutrality in South Africa's mineral sector is shaped by both international commitments and local governance frameworks. The interplay reveals a complex landscape that requires ongoing adaptation and commitment to sustainable practices. The South African government controls mineral resources and has established regulations aimed at sustainable mining practices. These regulations are designed to mitigate environmental impacts and promote corporate governance in climate change responses (Odeku, 2015); (Mzenda, 2012).

CHALLENGES IN ACHIEVING CARBON NEUTRALITY

South Africa, like the rest of the world, is confronted with several significant challenges in its pursuit of carbon neutrality by 2050. These challenges stem from its economic structure, energy reliance, and environmental factors. South Africa's economy is heavily dependent on power generation that produces high carbon emissions, particularly from coal. This reliance complicates the transition to a low-carbon economy, as significant changes are required to reduce emissions from these sectors. Achieving net-zero emissions necessitates extensive transformations in South Africa's energy system. This includes a substantial expansion of renewable energy sources, increased electrification, and a gradual phasing out of coal power generation. The scale of these changes poses logistical and financial challenges.

Declining Productivity

The mining industry is grappling with the dual challenge of declining productivity and the need for greater operational efficiency, both of which are critical to achieving carbon neutrality. A 2015 McKinsey study revealed that productivity in the sector had dropped by 30% over the past decade, underscoring the urgency of the issue. At the same time, fluctuating commodity prices and rising labour costs are eroding profit margins, while deposits are becoming more difficult and expensive to access. These pressures are squeezing profitability, leaving companies with little choice but to address inefficiencies to remain competitive. Innovation is increasingly seen as the key to overcoming these hurdles, improving operational efficiency, protecting profit margins, and advancing carbon-neutral goals, all while maintaining the industry's social licence to operate (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2018).

Economic Disparities and Operational Efficiency

Globally, differences in economic development and legislative frameworks create disparities in carbon neutrality progress. Developed nations often have more resources to invest in clean technologies, while developing countries struggle with limited financial capabilities (Timofeev, 2022). South Africa's economy is heavily reliant on fossil fuels, which hampers its transition to renewable energy sources. This reliance has resulted in increased GHG emissions, complicating carbon neutrality efforts (Zhao, *et al.,* 2022). The South African mining sector is also struggling with energy efficiency, with many mines showing increased energy intensity rather than reductions (C.M.D & Langerman, 2023).

Technological and Collaborative Challenges

The transition to carbon neutrality requires innovative technologies and collaborative efforts. In SA, the slow adoption of carbon reduction technologies limits operational efficiency and productivity (Qingyu, *et al.*, 2024). Internationally, the need for strategic partnerships and integrated approaches is critical. Research indicates that collaboration in climate mitigation technologies can significantly reduce emissions (Zhang, *et al.*, 2023). While the challenges are daunting, they also present opportunities for innovation and collaboration, suggesting that a concerted effort can lead to improved operational efficiency and productivity in the pursuit of carbon neutrality.

Challenges Faced in Multi-Energy Systems

Multi-energy systems (MES) are essential for achieving carbon neutrality, but they encounter several significant challenges. MES involves the integration of various energy technologies, including renewable energy sources, energy storage, and smart grids. The complexity of integrating these diverse technologies can lead to operational inefficiencies and increased costs. Existing energy infrastructure may not be adequately equipped to support the transition to MES. Upgrading or replacing outdated infrastructure requires significant investment and time, which can delay the implementation of effective multi-energy systems. Current energy policies often focus on carbon emission reduction rather than a comprehensive approach to carbon neutrality. This misalignment can hinder the development and implementation of MES, as supportive policies are crucial for fostering innovation and investment in new technologies. The economic feasibility of implementing MES is a concern, particularly in terms of initial investment costs and the long-term return on investment. Stakeholders may be hesitant to invest in new technologies without clear financial incentives or guarantees of profitability (Alabi, *et al.,* 2023).

Corporate Governance in Sustainability

Effective corporate governance is required in steering organisations towards carbon neutrality, particularly in the context of South Africa's mining sector. It must evolve to incorporate ESG factors, addressing challenges such as executive compensation and accountability in sustainability efforts (Ji, 2023). Corporate governance should play a pivotal role in advancing carbon neutrality by managing risks, fostering transparency, engaging leadership, and promoting innovation, particularly in mining, where environmental impacts are significant, and the need for carbon neutrality is urgent.

The involvement of corporate boards and company executives in climate change discussions is essential as they influence the companies' strategic direction and ensure that sustainability is integrated into the core business model. This includes establishing climate change strategies and setting measurable goals for reducing emissions. When leaders prioritise sustainability, it fosters a culture of accountability and encourages employees to engage in sustainable practices. Corporate governance frameworks emphasise transparency and communication about climate change initiatives that can enhance stakeholder trust (Mzenda, 2012); (Scott, 2024). The traditional shareholder-centric governance model is increasingly seen as inadequate for promoting sustainability, necessitating a shift towards stakeholder-oriented approaches (Ji, 2023); (Johnston, 2023). Sustainable corporate governance often struggles to balance profit motives with social responsibilities, influenced by varying state regulations and the discretion allowed under the business judgment rule (Petrova, 2024). Companies that openly share their climate strategies and performance are more likely to gain support from investors, customers, and the community, which is vital for long-term sustainability. On a global scale, effective corporate governance can drive sustainability by aligning business practices with international standards and frameworks, such as the United Nations SDGs. Companies that adopt strong governance practices are better positioned to contribute to global sustainability efforts and respond to regulatory changes related to environmental protection. Corporate governance can also promote innovation in sustainable practices. By encouraging research and development in green technologies, companies can enhance their competitiveness and create value-added products that meet the growing demand for sustainable solutions (Mzenda, 2012).

Policy and Regulatory Challenges

A lack of cohesive global policies complicates efforts; countries differ in their legislative approaches to carbon neutrality, creating inconsistencies in implementation (Timofeev, *et al.*, 2022). Recent global crises, such as the COVID-19 pandemic, have disrupted progress, necessitating a reevaluation of carbon neutrality plans to incorporate emerging challenges (Jiang, *et al.,* 2022).

PATHWAYS TO CARBON NEUTRALITY

Opportunities for Carbon Neutrality in the Mining Industry - Short-term and Long-term Strategies

Achieving carbon neutrality requires a balanced approach, incorporating both short-term and long-term strategies. In the short term, immediate actions such as decarbonising the power supply, improving energy efficiency, and adopting renewable energy sources offer quick wins. These strategies are often supported by legal and regulatory frameworks that promote the electrification of key sectors and encourage fuel switching. On the other hand, long-term strategies focus on sustainable planning and future innovations, including the development of advanced energy technologies, infrastructure for renewable systems, and comprehensive policy frameworks that ensure ongoing progress toward carbon neutrality. The following pathways have been identified as crucial for this transition.

Innovations in Mining Technologies

Combined with an increase in energy efficiency and the production of more renewable energy, Carbon Capture and Storage is a promising technological chain that aims to prevent climate change by reducing anthropogenic CO_2 emissions into the atmosphere. As stated in the European directive on the geological storage of carbon dioxide, "monitoring is essential to assess whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and whether any identified leakage is damaging the environment or human health...." Another possible solution for CO_2 storage would be to chemically fix CO_2 into the carbonated minerals in mafic and ultramafic rocks (Jeandel & Philippe., 2012).

The use and integration of renewable energy-powered sources – as discussed earlier, such as solar and wind – into mining operations can drastically reduce carbon footprints. This shift not only supports sustainability but also enhances energy security and reduces operational costs in the long run. The transition to electric-powered mining vehicles reduces reliance on fossil fuels and lowers emissions. The adoption of electric trucks and loaders is a key opportunity for mining companies aiming for carbon neutrality while also reducing operational costs.

An example as reported by Subodh (2012) is an integrated and quantifiable plan for achieving 'carbon neutrality' in the global aluminium industry by advocating the five actionable steps shown in Figure 2.

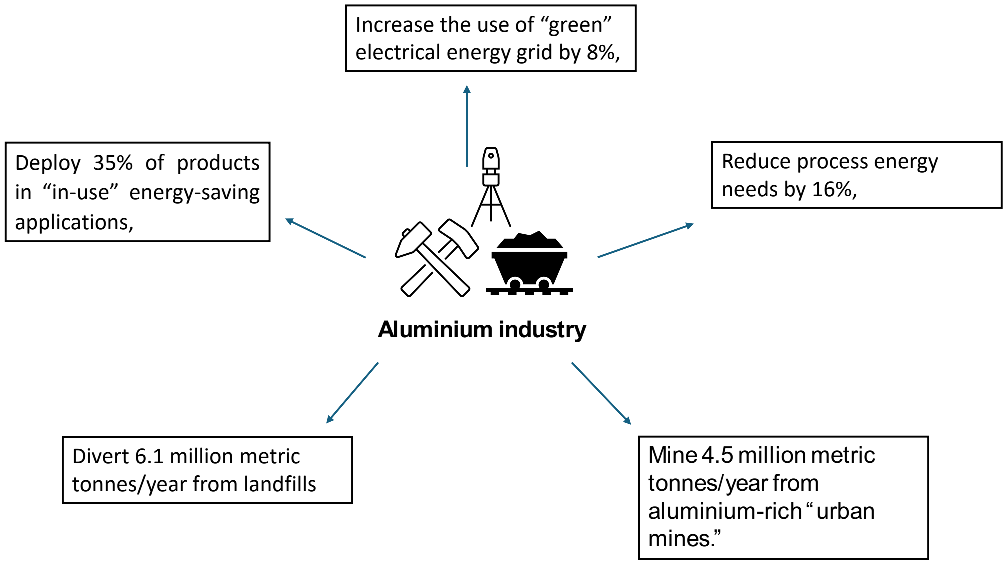

Figure 2. An integrated and quantifiable plan for achieving 'carbon neutrality' in the global aluminium industry (Subodh (2012).

Since it takes 20 times more energy to make aluminium from bauxite ore than to recycle it from scrap, the global aluminium industry could set a reasonable, self-imposed energy/carbon neutrality goal to incrementally increase the supply of recycled aluminium by at least 1.05 metric tonnes for every tonne of incremental production via primary aluminium smelter capacity. For the global aluminium industry, carbon neutrality is defined as a state where the total 'in-use' CO_2eq saved from all products in current use – including incremental process efficiency improvements, recycling, and urban mining activities – equals the CO_2eq expended to produce the global output of aluminium. Furthermore, the aluminium industry can and should take a global leadership position by actively developing internationally accepted and approved carbon footprint credit protocols (Subodh, 2012).

Energy Efficiency and GHG Reduction initiatives

Energy efficiency and GHG reduction initiatives in the mining sector are crucial for achieving carbon neutrality through technological upgrades, process optimisations, and reductions in process energy needs. Reducing process energy needs by 16% represents a concrete opportunity for energy efficiency improvements in mining operations.

The implementation of smart mining technologies, such as the Internet of Things and artificial intelligence (AI), in mining operations can optimise processes and reduce energy consumption. These innovations are essential for improving efficiency and supporting carbon neutrality initiatives in the industry. The use of autonomous vehicles and machinery in mining operations can significantly reduce carbon emissions by optimising fuel consumption and minimising human error. These technologies enhance efficiency and safety while contributing to carbon neutrality goals in the mining sector (KlemeŠ & Petar, 2006).

Adopting Circular Economy models

Adopting a circular economy model in mining focuses on reducing waste and maximising resource use through recycling and reusing materials. This approach is vital for achieving carbon neutrality by minimising the environmental impact of mining activities (Pan, *et al*., 2024). The following are a few examples of circular economy models that can be adopted to drive carbon neutrality.

Heterotrophic oxidation of waste organics is an approach which increases the supply of CO_2 for carbonation processes, representing a specific opportunity for integrating waste reduction and recycling in the mining industry. Several relevant acceleration examples include the bioleaching of magnesium silicates, biologically induced carbonate precipitation, and passive carbonation through tailings management practices. These examples are briefly explained below (Power, *et al*., 2014).

Biologically induced carbonate precipitation can enhance CO_2 fixation in mine tailings, contributing to carbon neutrality through innovative processing techniques. There is a potential to accelerate carbonation to create economically viable, large-scale CO_2 fixation technologies that can operate at near-surface temperature and atmospheric pressure.

Tailings management practices involve specific strategies to enhance passive carbonation in mine waste, directly addressing waste reduction and recycling opportunities in the mining sector. An example is passive carbonation occurring at the abandoned Clinton Creek asbestos mine, the active Diavik diamond and Mount Keith nickel mines, in Canada, however, there remains untapped potential for sequestering CO_2 within these mine wastes. Ultramafic and mafic mine tailings are a valuable feedstock for carbon mineralisation that should be used to offset carbon emissions generated by the mining industry. Scenarios for pilot-scale projects are proposed to move towards carbon-neutral mines.

Bioleaching of magnesium silicates is a specific innovation in mining technology that can enhance carbon mineralisation by utilising biological processes to extract valuable minerals while sequestering CO_2.

Green Mining Certifications

Green mine certifications involve specific assessment tools and criteria to evaluate mining practices, including construction levels and follow-up checks (Wang, *et al*., 2023). Obtaining green mining certifications can help companies demonstrate their commitment to sustainable practices and carbon neutrality. These certifications require adherence to strict environmental standards, promoting responsible mining operations that fulfil the requirements of ESG regulations leading to reduced carbon footprints and enhanced economic efficiency (Harit, 2023).

Sustainable Supply Chain Management

Developing a sustainable supply chain in mining involves sourcing materials responsibly and reducing emissions throughout the supply chain. This holistic approach is key to achieving carbon neutrality and enhancing corporate social responsibility.

- *Carbon Footprint Assessment Tools* - Utilising carbon footprint assessment tools allows mining companies to measure and analyse their emissions accurately. This data is essential for identifying reduction opportunities and tracking progress towards carbon neutrality goals.
- *Employee Training on Sustainability Practices* - Training employees on sustainable practices and carbon reduction strategies are vital for fostering a culture of sustainability within mining companies. This initiative empowers workers to contribute to carbon neutrality efforts effectively.
- *Partnerships for Sustainable Development* - Collaborating with governments, NGOs, and other stakeholders can enhance mining companies' efforts towards sustainability and carbon neutrality. These partnerships can lead to innovative solutions and shared resources for environmental stewardship.
- *Regulatory Compliance and Incentives* - Understanding and complying with environmental regulations, as well as leveraging incentives for sustainable practices, is crucial for mining companies. This compliance not only helps in achieving carbon neutrality but also enhances corporate reputation.

Strategic Implications for Mining Companies

Adopting carbon-neutral practices presents significant strategic implications for mining companies, primarily enhancing their sustainability and competitiveness. As the industry faces increasing pressures from resource depletion and regulatory demands for reduced GHG emissions, transitioning to low-carbon technologies is essential.

Mines are becoming not only more geographically isolated but also deeper. As deposits grow more challenging and costly to reach, companies must explore innovative ways to reduce operating expenses. In deep mines where conventional vehicles and generators are used, costs associated with ventilation and refrigeration can be substantial. Without sufficient investment in these areas, working at such depths becomes unfeasible. In addition to advancements in automation and digitisation, mining companies should consider adopting electric vehicles as a solution to this issue (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2018).

There is a need to integrate environmental accounting, a crucial component that allows companies to transparently disclose their carbon emissions and environmental impacts, aligning with national policies on carbon neutrality, and improving stakeholder trust, particularly as public and regulatory scrutiny intensifies (Jialu, 2024); (Syam, 2024). Research indicates that integrating green mining technologies can substantially reduce GHG emissions and energy consumption, enhancing environmental sustainability and economic efficiency (Onifade, *et al.*, 2024); (Qiang, 2023). Implementing climate-neutral practices within supply chains can optimise resource utilisation and lower GHG emissions, which is essential for achieving climate goals (Sharad, *et al.*, 2024). Exploring carbon storage in abandoned mines offers innovative pathways for resource development and participation in carbon markets, further supporting the transition to carbon neutrality (Xingxing, *et al.*, 2023). Collectively, these strategies do not only fulfil regulatory requirements but also position mining companies as leaders in sustainable development. Furthermore, effective management of structural capital is crucial, as it not only supports carbon neutrality but also enhances sustainable competitiveness, suggesting that strategic investments in green practices are essential for future viability (Wei, 2024). The implementation of innovative frameworks that incorporate environmental costs and carbon pricing into mining operations can optimise financial outcomes while minimising ecological impacts (Mirzehi & Afrapoli, 2024). The role of digital transformation and green finance, particularly through Fintech, is also pivotal in fostering innovation and aligning financial strategies with sustainability goals (Akhtar, *et al.*, 2024).

However, challenges remain, such as the need for effective environmental accounting disclosures to demonstrate commitment to carbon neutrality and the need for robust regulatory frameworks and stakeholder engagement to navigate environmental uncertainties (Jialu, 2024). The mining sector must navigate the trade-offs between economic viability and environmental responsibility, as seen in the lead industry, where declining demand due to carbon neutrality could impact prices and economic indices. Mining companies must adapt to avoid economic downturns linked to falling prices and supply-demand imbalances (Yufeng, *et al.*, 2024). Transitioning to low-carbon technologies, such as the electrification of haulage systems, can substantially reduce greenhouse gas emissions, although the initial capital costs present a barrier (Kemalcan, *et al.*, 2024). Embracing carbon-neutral practices is not only a regulatory necessity but it also a strategic move to enhance competitiveness, ensure the industry's future viability and enhance the mining sector's reputation and stakeholder trust.

Examples of Successful Strides Towards Carbon Neutrality.

In South Africa, several initiatives are making significant strides towards carbon neutrality in mining operations. One notable example is the Electric Mine Consortium, which brings together various mining companies to accelerate the transition to fully electrified mines, aiming for zero CO_2 emissions. This collaborative effort is crucial in addressing the industry's carbon footprint (Electric Mine Consortium, n.d.).

Anglo American has unveiled the world's largest hydrogen-powered mine haul truck prototype, marking a significant step towards carbon neutrality in mining operations. This 2 MW hydrogen-battery hybrid truck surpasses the power of its diesel predecessor and can transport a 290-tonne payload, forming part of Anglo American's nuGen Zero Emission Haulage Solution. The nuGen system integrates green hydrogen production, refuelling, and haulage directly at the mine site, with hydrogen generated using renewable energy sources. At Mogalakwena, Anglo American has constructed a zero-emission hydrogen production, storage, and refuelling facility, which includes the largest electrolyser in Africa, supported by a solar photovoltaic field, to power the hydrogen haul truck. This comprehensive solution underscores the company's commitment to reducing carbon emissions and advancing sustainable mining practices (Anglo American, 2022); (Viljoen, 2022).

Glencore, an Anglo-Swiss company, is exploring battery-powered trucks and equipment in its Onaping Depth mine in northern Ontario, Canada. Located 2500 metres underground, the ultra-deep nickel-copper-platinum group elements deposit offers ore grades that are double those previously mined in the area. The deposit depth previously made ventilation costs prohibitive, requiring additional surface openings to manage diesel fumes from traditional equipment. To address this challenge, Glencore is electrifying its fleet, using battery-electric trucks to haul ore to the surface. By transitioning to electric vehicles, the company can design a more efficient and cost-effective ventilation system that focuses on air quality, rather than diesel emission removal, significantly reducing energy requirements.

The electrification of the underground fleet also brings ancillary benefits, such as reduced noise, heat, and refrigeration needs. While the initial investment in electric equipment is higher, Glencore expects to cut ventilation and refrigeration costs by 50% over the mine's lifetime, thanks to lower energy consumption and cheaper electricity compared to diesel. This shift mirrors Goldcorp's approach at its Borden Lake deposit, where the Canadian company is developing the world's first diesel-free hard rock mine. By fully electrifying its equipment and working with manufacturers like Sandvik Mining and MacLean Engineering, Goldcorp aims to design a mine optimised for electric operations, reducing the environmental impact and ensuring sustainability.

In addition to operational savings, Goldcorp is focused on minimising the mine's environmental footprint to secure its social licence to operate, particularly with local First Nations communities. Switching to electric vehicles will eliminate GHG emissions associated with ore and waste rock movement, resulting in a 70% reduction in annual GHG emissions compared to a baseline mine. This initiative supports Goldcorp's goal to increase production by 20% across its operations by 2021 while meeting key climate change mitigation targets outlined in the SDGs (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2018).

C-NES is providing integrated carbon-neutrality solutions specifically tailored for the mining sector, focusing on renewable energy technologies such as biogas produced from cactus. The utilisation of biogas as a renewable energy source is particularly promising, as it helps reduce reliance on fossil fuels, thereby contributing to sustainability in mining operations (C-NES, 2024). Moreover, adopting renewable energy technologies, including solar and wind, is essential for sustainably powering mining operations.

Figure 3. Low-emission vehicle which is duel-fuelled using renewable biomethane and diesel (C-NES, 2024).

GOVERNMENT AND INDUSTRY ROLES

Achieving carbon neutrality requires collaborative efforts between government and industry, supported by robust policy frameworks. Governments are responsible for establishing legal frameworks and strategic plans that guide the transition to carbon neutrality. For example, Sweden's ambitious energy policies aim for zero net emissions by 2045, emphasising energy efficiency measures and integrating renewable systems at the city level (Maiullari, *et al*., 2022).

Establishing long-term policies that support sustainable energy practices and encourage investment in green technologies will help ensure a steady transition towards carbon neutrality. Examples such as carbon pricing or emissions trading system can drive immediate changes in how coal-based power systems operate. Figure 4 provides a visual representation of 26 regions aiming to achieve carbon neutrality through three approaches: existing laws, current policies, and proposed legislation. As depicted in the figure, the strength of commitment to carbon neutral targets decreases from existing laws to current policies, with proposed legislation being the least binding. Among the six regions with legally binding carbon neutrality goals, four are European Union members. Of the 26 regions, a significant majority (21 countries, including South Africa, the United Kingdom, France, and Japan) have set 2050 as their target year for achieving carbon neutrality (Zhao,*et al*., 2022).

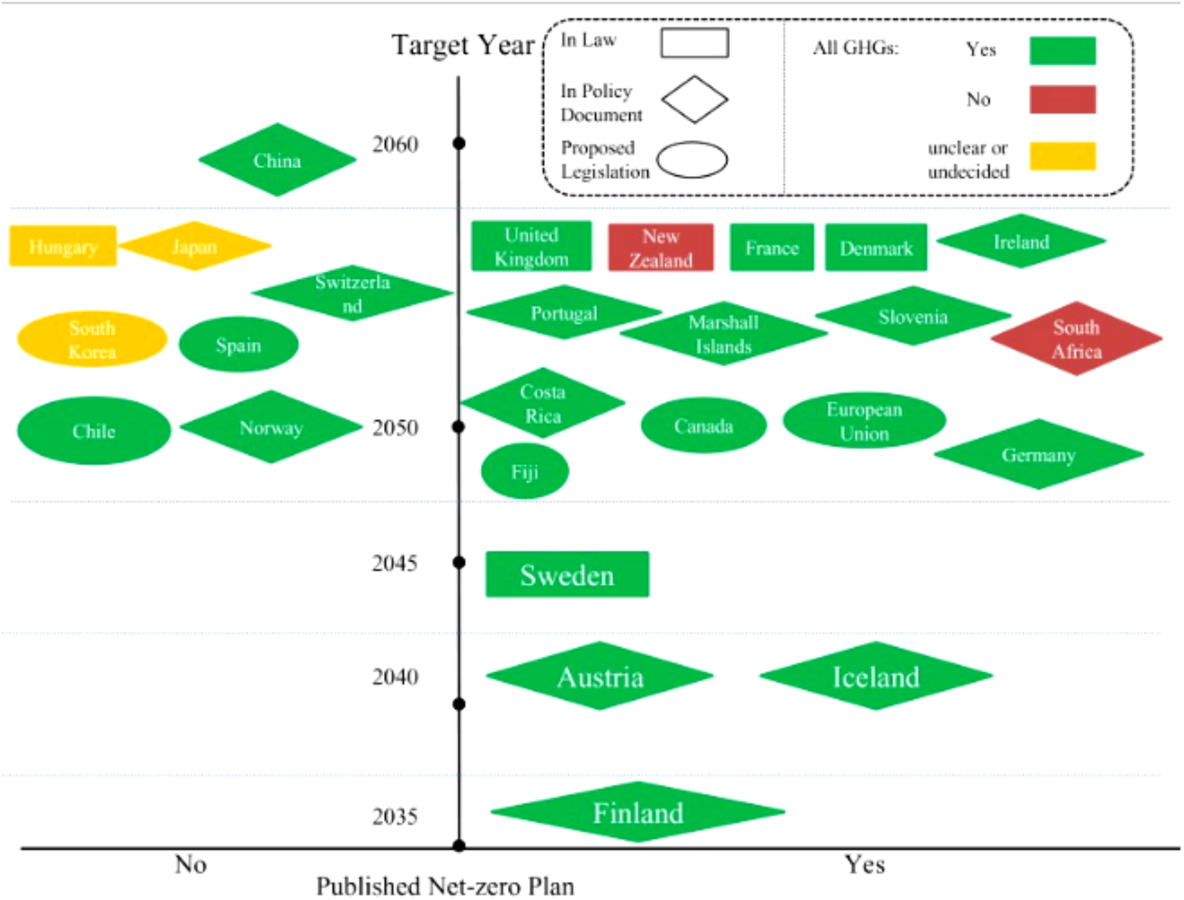

Figure 4. Visual representation of 26 regions aiming to achieve carbon neutrality through three approaches: existing laws, current policies, and proposed legislation (Zhao, *et al*., 2022).

Governments must adapt to the major changes in the mining sector driven by technological innovation. It is essential to ensure that the financial gains from improved efficiency and productivity are shared with communities, rather than solely benefiting companies. As automation and AI technologies are integrated, it is important to mitigate any potential negative impacts, such as reduced local employment and community investment. Governments should promote a fair distribution of the benefits from mineral development. Additionally, they should explore strategies for enhancing value addition, reforming fiscal policies to boost revenue, and transferring knowledge from the private sector to public entities. Investments in mining infrastructure should also benefit communities and other industries (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2018).

The industry is pivotal in the implementation of low-carbon technologies and innovations, such as the use of phase change materials in building applications to enhance energy efficiency and sustainability (Wenzhu, *et al*., 2024). Public support and community involvement are also crucial, as seen in Germany's neighbourhood-level initiatives, which effectively reduce emissions through the integration of renewable energy sources and low-carbon technologies (He, *et al*., 2023). The example of the Council of Scientific & Industrial Research's work on dual-fuel hydrogen internal combustion engines for the South African mining industry illustrates the importance of industry innovation in reducing emissions while maintaining operational continuity. This approach ensures compliance with international environmental standards and promotes the adoption of hydrogen technology, contributing to the economic and social sustainability of the mining sector.

Monitoring and Evaluation

Monitoring and evaluation have become more critical and essential in the journey toward carbon neutrality, as they provide frameworks for assessing progress. Governments and industries must establish robust monitoring systems to track the effectiveness of implemented strategies and ensure that they align with long-term sustainability goals.

For instance, the implications of technological innovation in the mining sector are profound, with automation and AI technologies poised to revolutionise the industry. However, governments must ensure that the financial benefits of these innovations are not captured solely by companies, but also contribute to community and environmental sustainability (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2018). Accurate satellite technologies and geofencing can also be employed to monitor environmental impacts and prevent the degradation of sensitive areas, such as wetlands.

CONCLUSIONS

Achieving carbon neutrality in the mining industry presents significant challenges and promising opportunities. The sector is confronted with declining productivity, squeezed profit margins, and increasing operational costs, all while striving to meet ambitious carbon neutrality goals. However, integrating innovative technologies, strategic partnerships, and robust policy frameworks offers a pathway to sustainable development.

MES facilitate the integration of diverse energy sources and technologies to significantly reduce carbon emissions and enhance energy efficiency. Innovations such as hydrogen-rich processes in metallurgical operations and repurposing abandoned mines for carbon storage represent transformative opportunities. These strategies do not only address emissions but also convert industry liabilities into valuable assets.

To advance toward carbon neutrality, the following are essential:

- Embrace Technological Innovation: Invest in and adopt new technologies that reduce emissions and enhance efficiency. Key innovations include hydrogen-rich processes and the use of abandoned mines for carbon storage.
- Strengthen Regulatory Frameworks: Implement and enhance regulations and incentives that support green practices and technological advancements. Developing policies that encourage innovation and sustainability is crucial.
- Foster Collaborative Efforts: Build partnerships among governments, academia, and industry stakeholders to drive innovation and resource efficiency. Collaboration will facilitate the sharing of knowledge and accelerate progress toward carbon neutrality.

- Promote Circular Economy Practices: Incorporate circular economy principles to maximise resource efficiency and minimise waste. This involves designing processes that reduce, reuse, and recycle materials, transforming waste into resources and enhancing overall sustainability.
- Government Incentives and Policy Support: Governments must continue to enforce stringent environmental regulations and offer incentives that encourage the adoption of low-carbon technologies and sustainable practices in the mining sector.
- Adapt Power Sector Investments: Adjust power sector investments to align with the shift toward renewable energy, ensuring that investment strategies support long-term sustainability goals.
- Promote Sustainable Supply Chain Management: Focus on reducing emissions throughout the supply chain, from sourcing to delivery, is essential for holistic sustainability in mining operations.
- Adopt Green Mining Certifications: Mining companies should pursue green certifications to solidify their commitment to sustainable practices, improving transparency and accountability.

By addressing these recommendations, the mining industry can navigate its path to carbon neutrality, turning current challenges into opportunities for innovation and sustainable growth.

REFERENCES

Akhtar, S., Tian, H., Alsedrah, I. T., Anwar, A., & Bashir., S. (2024). "Green mining in China: Fintech's contribution to enhancing innovation performance aimed at sustainable and digital transformation in the mining sector.". Resources Policy, 104968.

Alabi, T. M., Agbajor, F. D., Yang, Z., Lin, L., & Ogungbile, A. J. (2023). The strategic potential of the multi-energy system towards carbon neutrality: A forward-looking overview. Energy and Built Environment, 689-708.

Anglo American. (2022, May 6). Anglo American unveils a prototype of the world's largest hydrogen-powered mine haul truck - a vital step towards reducing carbon emissions over time. Retrieved from Press releases – 2022: https://www.angloamerican.com/media/press-releases/2022/06-05-2022#:~:text=Anglo%20American%20plc%20(%E2%80%9CAnglo%20American, PGMs%20mine%20in%20South%20Africa.

Barahira, D. S., Okudoh, V. I., & Eloka-Eboka, A. C. (2021). Suitability of crop residues as feedstock for biofuel production in South Africa: a sustainable win-win scenario. Journal of Oleo Science, 213-226.

C.M.D, M., & Langerman, K. E. (2023). Energy efficiency in the South African mining sector: A case study at a coal mine in Mpumalanga. Journal of The South African Institute of Mining and Metallurgy,

C-NES. (2024). Biogas-and-biomethane. Retrieved from https://www.c-nes.co/biogas-and-biomethane

Cox, B. B., Innis, S., Nadja, C., & Kunz., S. J. (2022). The mining industry as a net beneficiary of a global tax on carbon emissions. Communications earth & environment.

Electric Mine Consortium. (2024). Electrification. Retrieved from https://www.electricmine.com/

Guo, Q., Xi, X., Yang, S., & Cai, M. C. (2022). Technology strategies to achieve carbon peak and carbon neutrality for China's metal mines. International Journal of Minerals Metallurgy and Materials.

Harit, P. N. (2023). Green Mining: Environmental Ethics in Mining Engineering.

He, M., Nemeth, I., Blumenthal, A. v., Haupt, T., Stopper, J., & Jungwirth., J. (2023). Assessing pathways to carbon neutrality in a neighbourhood study in Germany. In Journal of Physics: Conference Series, 082010.

Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development. (2018). Innovation in Mining: Report to the 2018 International Mines Ministers Summit. Winnipeg: International Institute for Sustainable Development.

Janikowska, O., & Kulczycka, J. (2021). Impact of minerals policy on sustainable development of mining sector – a comparative assessment of selected EU countries. Mineral economics.

Jeandel, E., & Philippe., S. (2012). The relevance of geochemical tools to monitor deep geological CO2 storage sites. Geochemistry-Earth's System Processes, InTech, 81-104.

Ji, J. (2023). Corporate Governance and Sustainability. 297-314.

Jialu, X. (2024). Research on Environmental Accounting Information Disclosure of Mining Enterprises in China under the Context of Carbon Neutrality. Highlights in business, economics and management, 529-535.

Jiang, P., Sonne, C., & You, S.-q. (2022). Dynamic Carbon-Neutrality Assessment Needed to Tackle the Impacts of Global Crises. Environmental Science & Technology, 98.

Johnston, A. (2023). Integrating sustainability into corporate governance. 57-79.

Kemalcan, A., Şebnem, D., Evren, D. Y., & Fatih, A. (2024). A Systems Engineering Approach to Decarbonizing Mining: Analyzing Electrification and CO2 Emission Reduction Scenarios for Copper Mining Haulage Systems. Sustainability.

KlemeŠ, J. J., & Petar, S. V. (2006). Waste-to-Energy Technologies. Encyclopedia of Environmetrics.

Lucy, B. (2015). Renewable energy in South Africa's minerals-energy complex: a low carbon transition? Review of African Political Economy, 245-261.

Maiullari, D., Palm, A., Wallbaum, H., & Thuvander, L. (2022). Pathways towards carbon neutrality: A participatory analysis of the Gothenburg's energy plan. IOP Conference Series: Earth and Environmental Science,

Mirzehi, M., & Afrapoli., A. M. (2024). A novel framework for integrating environmental costs and carbon pricing in open-pit mine plans: Towards sustainable and green mining. Journal of Cleaner Production, 143059.

Montmasson-Clair, G. (2015). The Interplay between Mining and Green Economy in South Africa. An Energy Lens.

Moorosi, L., & Vusi, G. (2021). Social and economic effects of illicit financial flows in South Africa. In Illicit Financial Flows from South Africa (pp. 48-62).

Mzenda, V. (2012). Climate change governance in the South African mining sector. Journal of Corporate Citizenship, 45-67.

Odeku, K. O. (2015). Regulation of Mining Activities in South Africa: Prospects, Challenges and Pitfalls. Journal of Human Ecology, 33-39.

Onifade, M., Zvarivadza, T., Adebisi, J. A., Said, K. O., Dayo-Olupona, O., Lawal, A. I., & Khandelwal, M. (2024). Advancing toward sustainability: The emergence of green mining technologies and practices. Green and Smart Mining Engineering, 157-174.

Pan, H., Sun, Y., Wang, M., Dong, Z., Wang, Z., Zhang, Y., & Zhang, X. (2024). Rising from the ashes: Transitioning towards carbon neutrality through the pathways of circular economy agglomeration. Ecological economics.

Papafloratos, T. M. (2023). Sustainable Development Goals and the Mining Industry, Contributions to Management Science. In Sustainable International Business. Springer International Publishing.

Petrova, A. (2024). Sustainable corporate governance of American social enterprises under the pressure of new trends.

Power, I. M., McCutcheon, J., Harrison, A. L., Wilson, S., Dipple, G. M., Kelly, S., . . . Southam, G. (2014). Strategizing carbon-neutral mines: a case for pilot projects. Minerals,, 399-436.

Qiang, L. (2023). Analysis of Carbon Sequestration Effects in Green Mining Construction. Scientific Journal of Technology.

Qingyu, Z., Wong, C. W., & Klassen, R. (2024). Carbon neutrality: Operations management research opportunities. Journal of Operations Management, 344-354.

Sajid, M. J. (2019). Calculating inter-sectoral carbon flows of a mining sector via hypothetical extraction method. Journal of Mining and Environment.

Scott, P. (2024). Corporate governance and sustainability.

Sharad, S., Rajesh, S., Ruchi, M., & Nachiappan, (. S. (2024). Developing climate neutrality among supply chain members in metal and mining industry: natural resource-based view perspective. The International Journal of Logistics Management.

Subodh, D. (2012). Achieving carbon neutrality in the global aluminium industry. JOM, 285-290.

Syam, M. A. (2024). Carbon accounting: Its implications on accounting practices and corporate sustainability reports. International Journal of Economics and Financial Issues, 178-187.

Timofeev, G., Podkolzin, P., & Gladilin, D. (2022). Global trends and challenges of achieving carbon neutrality. Russian Journal of Resources, Conservation and Recycling.

Ting, M. B. (2015). Historical review of the relationship between energy, mining and the South African economy.

Ulrich, H. S., Trench, A., & Hagemann, S. (2022). Gold mining greenhouse gas emissions, abatement measures, and the impact of a carbon price. Journal of Cleaner Production.

Viljoen, N. (2022, November 21). Bringing the South African hydrogen valley concept to reality, Anglo American and partners have successfully launched the world's largest hydrogen-powered vehicle. Retrieved from Driving the Hydrogen Economy in South Africa: https://www.angloamerican.com/our-stories/innovation-and-technology/driving-the-hydrogen-economy-in-south-africa

Wang, Y., Peng, S., & Wang, L. (2023). Green Mine Special Tools." In Guidelines for Green Mine Construction and Management. Springer Nature Singapore, 159-172.

Wei, F., Han, J., & Xu, W. (2024). Exploring the nexus between structural capital, carbon neutrality and sustainable competitiveness: Evidence from natural resource exploitation in the post-COVID-19 era. Resources Policy.

Wenzhu, L., Yao, X. Z., Pu, Y., & Wang, S. (2024). "Pathways to Carbon Neutrality in the Built Environment: Phase Change Materials. Green Carbon.

Xingxing, L., Tong, Z., Liang, Y., & Juejing, F. (2023). Prospects for the transformation and development of carbon storage in abandoned mines of coal enterprises from the perspective of carbon neutrality. International Journal of Coal Science & Technology.

Yang, I., Jayhyun, P., & Kim, Y.-T. (2022). Recommendations for Carbon Neutrality and ESG Management in the Mining Industry. Journal of the Korean Society of Mineral and Energy Resources Engineers.

Yufeng, W., Haixia, L., Yifan, G., Huijing, H., Guofu, Z., & Qiuyan, Y. (2024). How can the lead industry improve sustainability based on the resource-economy-carbon nexus system? Sustainable Production and Consumption.

Zhang, X., Shi, X., Khan, Y., Hassan, T., & Marie., M. (2023). Carbon neutrality challenge: Analyse the role of energy productivity, renewable energy, and collaboration in climate mitigation technology in OECD economies. Sustainability, 3447.

Zhao, X., Ma, X., Chen, B., Shang, Y., & Song., M. (2022). Challenges toward carbon neutrality in China: Strategies and countermeasures. Resources, Conservation and Recycling.

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Systematic review and industry implications of carbon emission models for underground metal mines

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This paper examines journal articles published between 1994 and 2024 and provides a systematic overview of carbon emission models in underground metal mines using bibliometric statistical approaches. Through a thorough analysis of peer-reviewed journal papers and conference proceedings, with a focus on data-driven models, the study highlights trends, techniques, and datasets used in the mining and energy sectors. The research critically assesses the development and application of carbon emission models, revealing important advancements while identifying knowledge gaps. By considering key factors such as the type of datasets used, carbon sources considered, spatial modelling, and the models' effectiveness in predicting and reducing emissions in underground mining activities, the study provides a comprehensive understanding of the field. The research aims to contribute valuable insights into the creation and utilisation of carbon emission models, with the intent of guiding future research and improving decision-making in the mining industry. Ultimately, this work promotes the adoption of more sustainable practices by identifying effective modelling approaches that can support efforts to reduce carbon emissions. The findings offer a foundation for refining carbon management strategies in underground metal mines, with implications for both industry practices and environmental policy.

INTRODUCTION

South Africa's energy landscape, heavily dependent on coal, contributes significantly to global carbon emissions, with coal-fired power plants accounting for over 80% of the nation's electricity (Yu-Chia Ko, 2021). The mining sector, responsible for 6% of South Africa's industrial greenhouse gas (GHG) emissions (Hofmeyer, 2019), plays a pivotal role due to its reliance on coal-powered energy. Despite some progress in reducing emissions since 2008, South Africa remains the leading carbon emitter on the African continent (Ayompe, *et al.*, 2021). Projections suggest emissions will continue to rise without substantial intervention, particularly in the mining sector, where sustainable practices are urgently needed.

National policies such as the National Environmental Management: Air Quality Act (No. 39 of 2004), National Climate Change Response White Paper (2011), Carbon Tax Policy Paper (2013), Integrated Energy Plan (IEP) (2016), National Greenhouse Gas Emission Reporting Regulations (2017), Low Emission Development Strategy (LEDS) 2050 (2018), Integrated Resource Plan (IRP) (2019), Carbon Tax Act (No. 15 of 2019), Climate Change Bill (2022), and National Development Plan (NDP) 2030 aim to mitigate carbon emissions and promote a green economy. However, these policies often lack specific methodologies for calculating emissions, leaving gaps in how emissions are modelled and reduced.

On an international level, frameworks like the International Council on Mining and Metals (ICMM) Principles, particularly Principle 6 on environmental performance, and ISO standards such as ISO 14067:2018 (Greenhouse gases—Carbon footprint of products), ISO 50001:2018 (Energy management), and ISO 14097:2021 (Greenhouse gas management) offer additional guidelines. These provide crucial support for improving carbon management and encourage the adoption of low-carbon technologies.

The objective of this research is to fill these gaps by systematically reviewing carbon emission models in underground metal mining, focusing on data-driven models. By analysing trends, techniques, and datasets used in carbon modelling, this study seeks to improve decision-making and promote sustainable practices in the mining industry. The insights gained can inform both national and international carbon reduction strategies, supporting South Africa's transition to lower emissions and alignment with global carbon policies.

Previous reviews on emission models

a. Traditional vs Machine Learning data models

Several preliminary themes have been identified as being relevant to the modelling of carbon emissions. In the area of carbon emission prediction models, research shows that existing methods for predicting carbon emissions can be divided into two categories. These methods are the Traditional Data Model and Machine Learning Data Model both used for prediction (Li, *et al.*, 2021). The field of Traditional Data Models (Li, e*t al.*, 2021) identifies the most common methods to be the LMDI Decomposition Model used mostly in the fields of environmental sciences and engineering, the STIRPAT model derived from the IPAT model and used in population studies, energy studies, marketing, agriculture, and in the interaction of various factors within an economy. There is also the Autoregressive Distributed Lag Model in the category of Machine Learning Data Models (Li, *et al.*, 2021). These methods are further categorised as using indirect variables as they select key indirect variables to analyse their relationship with carbon emissions (Chen, *et al.*, 2022). Common variables considered under these methods include population, living standard, gross domestic product (GDP), energy use intensity, and the carbon emission factor. Under the category of Machine Learning methods, studies identify the Time Series Model, Grey Factor Model, and the Artificial Neutral Network Model (Li, *et al.*, 2021). Prevalent Time Series Models include the Moving Average Model, the Autoregressive Model, the Auto Regressive Moving Average Model, as well as the Auto Regressive Integrated Moving Average (ARIMA). The Grey Forecasting Model is mostly suited when predictions are made in systems with uncertain influencing factors. When the Artificial Neural Network Model is applied in predicting carbon emissions, the model proves to be more accurate for simple data models as opposed to complex data models, proven by (Yang, *et al.*, 2019) through reducing the complexity of the data set to achieve a more accurate air quality evaluation accuracy. (Liu, *et al.*, 2014) developed a prediction model based on a grey model GM(1,1), a second-degree polynomial regression approach and an ARIMA model to analyse the trend in community energy internet in the thermal power industry. The prediction model was applied to forecast future data and did well in its empirical analysis (Sun & Huang, 2022). (Wang & Lin, 2017) integrated the vector autoregressive model with the STIRPAT model to precisely predict carbon emissions from China's business sector in 2030.

When (Li, *et al.*, 2021) studied the literature of current research on carbon emission models in China and the rest of the world from 2011 to 2020, they identified a total of 15 600 publications from the Chinese database, and 17 500 articles from the rest of the world. The findings demonstrated a consistent increase in publications in China and the rest of the globe, pointing to a redoubled commitment to efforts to reduce carbon emissions internationally. From the research that presently exists it is apparent that the models discussed are compounded and used in combination to achieve complementary results.

On the theme of carbon emission estimation and calculation models, (McDonough, *et al.*, 2016) attempted to estimate the CO2 levels in a karst environment by studying the behaviour of carbon dioxide concentration in a cave. The main factors affecting CO2 concentration in a cave are ventilation, seasonal change or climate and the presence of ground water. The source of carbon is identified to be organic and inherently from the cave soil and dependent on soil properties (McDonough, *et al.*, 2016). When estimating carbon footprints, (Pandey, *et al.*, 2011) considered various methods of computing

carbon footprints and initially identified greenhouse gas (GHG) emissions to be significant in the lifecycle approach, as these must first be estimated and then added during the life cycle assessment (McDonough, *et al.*, 2016) – a process that (Pandey, *et al.*, 2011) technically define as carbon accounting. Other traditional approaches presently used in estimating GHGs include the bottom-up or process-analysis method as well as the top-down or economic input-output method (EIO) of estimation. The bottom-up strategy categorises the emission sources for easier measurement and the top-down method is extended and applicable to environmental factors in carbon footprint analyses (Pandey, *et al.*, 2011). In recent studies these two methods are integrated to form a hybrid life cycle assessment technique.
To calculate carbon emission levels, (Li, *et al.*, 2022) established the B-R model as a carbon emission accounting model to calculate emissions for a fully automated underground mining method. The authors initially identified carbon emission sources from preparation, operation and the final stage of the mining process and established an accounting model for each step. The carbon sources include fuel combustion, torch combustion, GHG fugitive, net purchased electricity and net purchased heat (Li, *et al.*, 2022). The IPCC default method and the China Coal Production Enterprises Greenhouse Gas Emissions Accounting Methodology and Reporting Guide validates the model to be accurate and for its accuracy to lie within the international error range of 5%. The IPCC method uses direct influencing variables to develop carbon emission calculation models. Other similar methods include the Regression method, System Dynamics method and the Scenario Analysis methods (Chen, *et al.*, 2022). The default lower-level IPCC method is simplistic in its use and operation and commonly used in roughly estimating carbon emissions. To maintain the accuracy of the computation of carbon emissions, it does not, however consider the resources of various regions. In general, at the opposite end, the higher-level IPCC default technique is regarded as too complicated to be practical.

(Zhang, *et al.*, 2020) point out that artificial intelligence algorithms are becoming increasingly popular in the field of carbon emission prediction models because of their strong learning and self-organising capabilities. (Wu, *et al.*, 2016) leveraged previous developments by creating a dynamic algorithm that forecasts carbon emissions using Monte Carlo simulations. These methods were then used by (Niu, *et al.*, 2020) to project China's total and intensity of carbon emissions over a 25-year period.

When estimating GHG emissions for the full supply chain of the power industry, (Chen, *et al.*, 2022) developed an original method based on a multi-scenario analysis of electricity consumption. Using the G province of China (Chen, *et al.*, 2022) device, the model was based on composition and transport methods of the entire power industrial chain's carbon emissions, considering methods for calculating the carbon emissions from both overall electricity consumption and electricity network losses. The paper further established the carbon emission coefficient by econometrics principles. Forecasting in the early phases was done using econometric models. In addition, this paper develops the reference scenario, the low carbon scenario, and the security constraint scenario to carefully examine alternative strategies for future GHG control (Chen, *et al.*, 2022). A quantitative assessment is done of the correlation between electricity usage and CO2 emissions from the power system. The results show that the province of G could achieve its maximum CO2 emissions from energy consumption most successfully under the low carbon scenario. In contrast to earlier studies in this field that mainly focused on indirect variables that have indirect impacts on carbon emissions at a macro level, the study is significant for the research proposed because it takes both direct and indirect carbon emission factors into account in the calculation model. In identifying direct and indirect carbon sources and developing computation models for each type of source, the methodology used in the study is consistent with the goals of the proposed study.

(Tsokos & Xu, 2009) use differential equations to model carbon emissions with the focus on defined variables that are attributable to C02 emissions. The study uses US data from 1950 to 2005. Multiphase fuels, specifically gas, liquid, and solid phase fuels, as well as additional variables including gas sparkles, concrete, and stockpiles are among the factors defined in the study (Tsokos & Xu, 2009). The authors developed differential equations for each of the variables attributable to CO2 emissions as well as an equation for the total of the variables combined. The generated models forecast the variables' rates of change for projections of 10, 20, and 50 years.

b. Monte Carlo simulation
Where there isn't enough carbon emission data available to apply the traditional or machine learning techniques outlined in the literature, Monte Carlo simulation can be used instead. What is known about Monte Carlo techniques is that when the model's inputs are random variables rather than fixed values, Monte Carlo methods are utilised to mimic specific phenomena (Tsiakmakis, *et al.*, 2016) and enable the evaluation of a system's probability under random influences (Pfaff, 2023), such as when estimating and forecasting CO2 emission levels. To obtain a Monte Carlo simulation for CO2 emissions, numerous numerical simulations of CO2 readings with various parameters can be simulated.

When modelling carbon dioxide with Monte Carlo simulation techniques, (Kumar, *et al.*, 2011) use Direct Simulation Monte Carlo (DSCM) code based on the Statistical Modelling in Low-Density Environment (SMILE) analysis to simulate carbon dioxide evaporation at high-pressures. The study uses the Bhatnagar-Gross-Krook (BGK) statistical approach, with the DSCM solution serving as the benchmark. For three scenarios of static pressure ranging between 1 and 5 bar, the study propagates uniform evaporation flow of CO2. Motion, particle indexing into cells, binary collisions, and macro parameter sampling are the fundamental steps highlighted in the DSCM simulation. In GHG reduction research, three-dimensional geologic modelling and grid-based Monte Carlo simulation are used to evaluate the many stages of fluid carbon dioxide sequestration capacity of saline formations in a basin in Korea (Jai-Yong, *et al.,* 2018). A series of grid-based Monte Carlo simulations are run 1000 times using Grid Converter and CO2-STOR to estimate the theoretical and practical multi-fluid-phase. CO2- STOR is a probabilistic evaluation approach for multi-fluid-phase theory and practice (Jai-Yong, *et al.*, 2018). Numerous probabilistic analyses are carried out in the study to predict multi-fluid-phase where grid-based simulations using Monte Carlo methods and multidimensional geological modelling are used in succession as a connected technique. In studies related to science and technology for the built environment (Liang, *et al.*, 2020) performed a total of 3000 simulations with input parameters such as room area, indoor temperature, air exchange rate, and weight and height of room occupants over a year to determine whether the gas carbon dioxide is a reliable predictor of formaldehyde in homes.

When analysing chemicals for study, (Kohmuean, *et al.*, 2021) observed CO2, CH4, and their mixture capture in porous carbons using Monte Carlo modelling and experimental testing. The adsorption isotherms in the study are calculated using the Grand Canonical Monte Carlo simulation using the Metropolis technique in Monte Carlo simulation. Using Kinetic Monte Carlo (KMC) simulation and first principles calculations in a statistical uncertainty in chemical physics, (Kopac, *et al*., 2017) simulated the production of methanol on copper using hydrogen and carbon dioxide reactors. Using the graph theoretical KMC software package, (Kopac, *et al*., 2017) simulated the process at seven different temperatures and four different pressures, emphasising that density function theory and microkinetic modelling alone cannot be used to assess different catalytic processes at different settings. In chemical engineering studies involving the use of a metal-organic framework to increase the generation of formic acid from carbon dioxide, (Wasik, *et al.*, 2023) perform Monte Carlo simulations with Brick-CFCMC and the RASPA software package in a statistical ensemble in the bulk-phase and confinement, respectively.

To introduce a new emission certificate procedure for light-duty transport vehicles from Europe, (Tsiakmakis, *et al.*, 2016) used CO2MPAS to perform Monte Carlo simulations of the potential effect of the new certificate on fleet carbon dioxide emissions. The CO2MPAS model utilised in the transportation research study is a system which integrates fully constructed automobile simulation models with broad-application emissions models. In the field of carbon sequestration (Takashi & Kozo, 2011) employed an adaptive evolutionary Monte Carlo algorithm to optimise well placement for geological carbon dioxide sequestration. The TOUCH2 and ECO2N modules are utilised in the study to simulate carbon flow, while the AEMC algorithm is employed to provide the optimisation of well placement. The amount of CO2 captured in the target area was specified by (Takashi & Kozo, 2011) as the function that needed to be optimised through the secondary mechanisms. The grid indices of the injection well are the independent variables. (Takashi & Kozo, 2011) demonstrate the AEMC algorithm's effectiveness by comparing it to an exhaustive simulation.

METHODS

To give a clear overview of the review process, this search technique combines bibliometric analysis, information summary, and a systematic review of existing literature. A simplified illustration of the process is shown in Table 1.

Because they are the most often searched sources for recent and relevant scientific literature, Scopus and Web of Science were the electronic databases that were specially selected. The author used four layers of filters during the search procedure. Every database was initially filtered according to the type of document. The author selected journal articles as the document of choice. Filtering the first set of results based on Scopus categories was the second step. The author sorted the databases by year range in the third stage, choosing years between 1994 and 2024. The last step was to refine the earlier search results by eliminating any publications without an author, affiliation, or reference list. For the rest of the search phrases in Table I, the author used the same search process. Appendix I contains the search results for these searches.

Search methodology
The author modified the data extraction approach used by (Mahboob, *et al.*, 2022) to analyse the data using the titles listed in Appendix II. The author then created a series of questions to accurately gauge the impact of the carbon models that have been documented in the literature.

Table I. Conceptualised from (Padhan & Bhat, 2023)

Database	Scopus	Web of Science
Search string	TITLE-ABS-KEY ("carbon emission models" OR "GHG emission models" OR "CO2 emission models") AND TITLE-ABS-KEY ("underground emission modelling" OR "underground GHG modelling" OR "underground CO2 modelling")	TITLE-ABS-KEY ("carbon emission models" OR "GHG emission models" OR "CO2 emission models") AND TITLE-ABS-KEY ("underground emission modelling" OR "underground GHG modelling" OR "underground CO2 modelling")
Filters applied	First filter-stage: Document type, articles Results: 66,887 journal articles in English Second filter-stage: Scopus categories Results: 17,418 articles from relevant subject areas Third filter-stage: Years 1994 - 2024 Results: 17, 205 articles were selected Fourth filter-stage: Exclusion of articles without author's name, affiliations, ref list, abstracts Results: 17,052 journal articles were finally selected for analysis	First filter-stage: Document type, articles Results: 72,945 journal articles in English Second filter-stage: Scopus categories Results: 41,456 articles from relevant subject areas Third filter-stage: Years 1994 - 2024 Results: 41,302 articles were selected Fourth filter-stage: Exclusion of articles without author's name, affiliations, ref list, abstracts Results: 41,302 articles were finally selected for analysis
Database categories	Environmental science, energy, engineering	Environmental science, energy fuels, Green sustainable science technology, Engineering environmental, Environmental studies
Language	English	English
Source type	Article	Article

Research questions
The following questions are addressed by examining how underground carbon emission models have evolved between 1994 and 2024:

1. Is there a spatial model included in any of the carbon emission models?
2. Which error assessment technique was applied when building the model?
3. Which kind of dataset—real or synthetic—was used to create the model?
4. Which techniques have been used in order to validate the emission model?
5. Which carbon sources—direct and indirect—are incorporated into the model?

RESULTS AND DISCUSSION

The findings of the search process revealed that more articles were published in the fields of general carbon emission models and CO2 emission models than for any other search term after all six search phrases indicated in Table 1 had been used. Less research was done throughout the study period with an emphasis on underground emission models and underground CO_2 modelling, although there appears to be a consistent flow of papers under GHG emission models. Figure 1 presents a summary of these findings. Figure 2 illustrates that between 1994 and 2024 surface environments saw a greater number of publications on carbon and GHG emission models, while underground environments—particularly underground mining environments—saw little to no attention. The summary of the database results is provided in Appendix I.

To address the challenge of locating relevant studies that examine carbon emission models in underground working areas, the author opted to include an additional search string in the list presented in Table 1. In this last phase, the database category Environmental Science was searched using the final search phrase, "modelling AND carbon AND emissions" as well as "modelling AND greenhouse gas AND emissions". The author then applied the original four layers of filters. Figure 3 contains the final list of studies that were chosen from the two searches. In this final search, the author selected a total of 11 articles to review. The selection criteria and results for this list is provided in Appendices II and III respectively.

Upon scrutinising the chosen research works for publications on carbon emission models that included spatial models, the author discovered that four articles contained some sort of spatial model. In one instance, the authors displayed the predicted temperature contours using average-diffused model in a study modelling heat and carbon monoxide in an underground car park. Meanwhile, another study contains a spatial distribution of carbon emission efficiency and carbon emission intensity. The third study included a heat map of CO emissions, a spatial pattern of CO emission, and a spatial pattern of comprehensive evaluation of CO emissions, all from motor vehicles. The last study contained geographic information system (GIS) surfaces of spatial CO2 distribution in the vegetation and heating seasons produced from the Inverse Distance Weighting interpolation method, the tension spline radial basis function interpolation method, as well as the Voronoi diagram with the Thiessen polygons method. Additionally, the studies identified the following widely used techniques for both quantitative and qualitative modelling of carbon emissions:

a. B-R carbon accounting model
b. Computational fluid dynamics (CFD)-based numerical models
c. Quantitative calculation models
d. Factor analysis
e. Differential equations

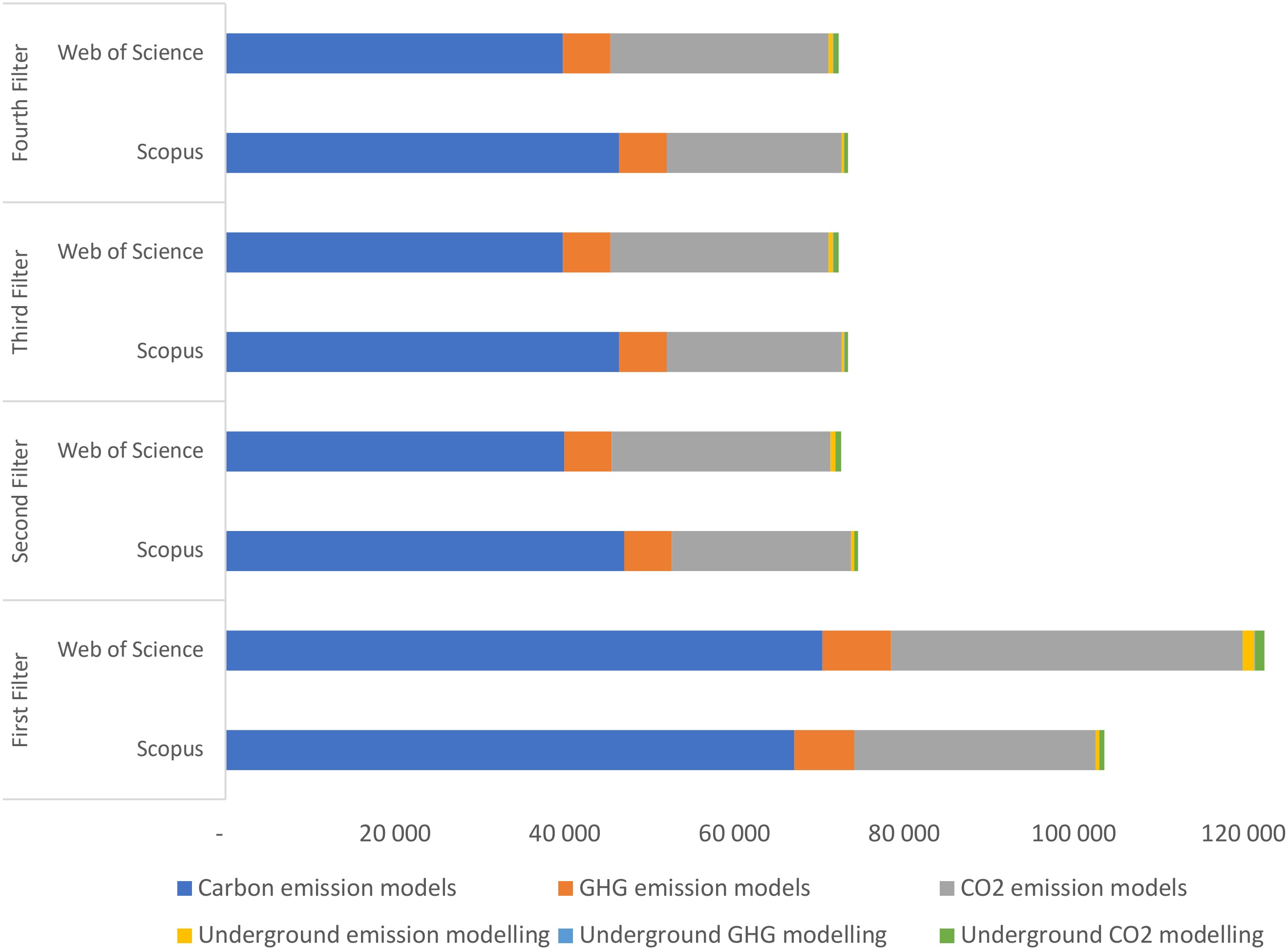

Figure 1. Search results from Scopus and Web of Science.

Literature review expansion

In the literature, the B-R model was created as a method for calculating carbon emissions from an underground, fully automated mining process, and followed this equation to denote the total carbon emissions from underground fully mechanised mining processes (Li, *et al.*, 2022):

$$E = Ef + Et + Es + Eg$$

Carbon emissions from coal mining and falling, coal transportation, roof support, and treatment of the coal mine area are among the factors taken into account. At the Jinda coal mine in China, the B-R model created by (Li, *et al.*, 2022) has been successfully implemented, demonstrating its efficacy in predicting emissions under various operating conditions. Because of its versatility, this model can be customised to fit various mining environments, which makes it a useful tool for improving environmental performance to comply with regulations. However, its applicability in regions with different data availability may be limited due to its reliance on specific datasets from the listed mining activities. Further research may concentrate on strengthening the adaptability of the model to suit various mining conditions.

In contrast, one study uses a combination of numerical models based on CFD to simulate carbon monoxide concentrations and temperature. Without using real data, the mathematical models mimic the flow of heat and carbon monoxide. These models are useful for assessing and designing efficient mechanical ventilation systems, as demonstrated by the successful application of the models to predict air quality in an underground parking garage in the same study. However, its focus on moving vehicles alone may limit its applicability in studying emissions from stationary underground sources. In the future, these models might be modified to account for stationary emissions, like those from industrial processes or underground mining equipment. Furthermore, incorporating real-world data from underground mining environments to the simulations could improve their reliability and accuracy allowing for air quality prediction and optimising ventilation systems. Examining the possibility of combining machine learning methods with CFD models may also improve prediction performance and offer more dynamic approaches to controlling emissions in underground environments.

Yet, a study utilising real data for quantitative analysis was also identified. In this study, actual historical carbon emission data from China's G province is simulated over a span of 10 years. The simulation analysis focuses on several scenarios of energy usage. Although none of the research included a spatial model of carbon emissions, one study did provide a spatial representation of carbon emission efficiency. The spatial model was constructed using actual historical panel data from 2000 to 2016, which was gathered for China and its provinces. In this study the authors created mathematical models for the several components that contribute to carbon emission efficiency using the factor analysis method.

In a different approach that considers contributing factors, a set of differential equations is employed to model carbon emissions. Each source of CO2—such as gas fuels, liquid fuels, solid fuels, cement production, gas flaring, and bunker fuels—is represented by a distinct mathematical equation. This results in a series of differential equations, each corresponding to one of these six variables. The cumulative emissions, expressed in metric tonnes, are then derived from the resulting differential equation, which integrates the contributions of all six sources as follows (Tsokos & Xu, 2009):

$$E(t) + E0\ (t) = -3.73335 \times 1010 + 5.6403 \times 107 \times t - 28405.687 \times t^2 + 4.771 \times t^3$$

There author found the following real-world scenarios where differential equations were used to calculate carbon emissions, such as in a climate change case study where (Donald, *et al*., 2024) developed a mathematical model to estimate CO_2 emissions from vehicles.

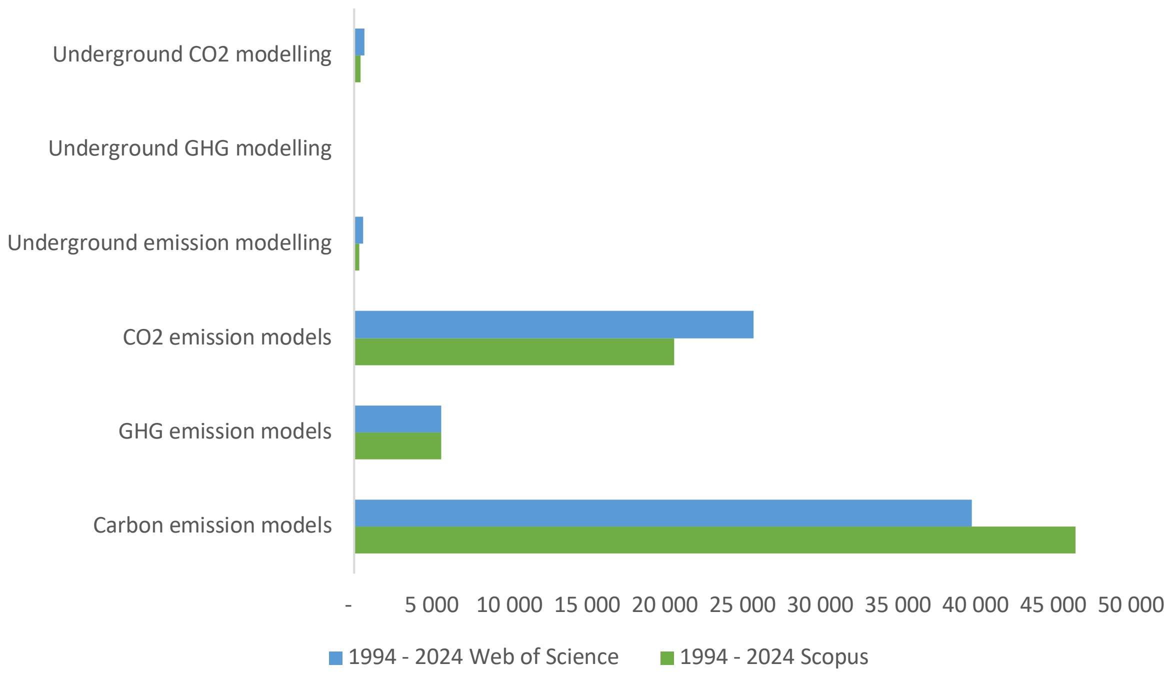

Figure 2. CO2 and GHG emission articles published between 1994 - 2024 on Scopus and Web of Science.

The study took into account factors like human population, economic activity, forest biomass, and vehicle populations, allowing for the quantitative analysis of atmospheric CO2 with these system parameters. The model served as a framework for strategies aimed at mitigating the effects of higher carbon dioxide emissions from vehicles. Comparably, differential equation models are frequently used in the energy sector to simulate industrial emissions, enabling dynamic prediction of those emissions dependent on operational conditions. A two-dimensional differential equation model was applied in a related study by (Han, *et al*., 2022) to forecast the time of peak carbon dioxide emissions and carbon neutralisation. Based on China's annual growth rate of emissions and annual growth rate of carbon absorption, the study established a relationship between carbon emission and carbon absorption. China aims to achieve carbon neutrality by 2060 and peak CO2 emissions by 2023 (Han, *et al.*, 2022). The model's predictions will assist policy makers in developing efficient strategies that improve the natural growth rate of carbon absorption and carbon emission reduction technology.

The author notes that, although it is outside the boundaries of the study, differential equation models can also be used to predict emissions from farming and livestock (Xiao & Duan, 2020), optimise traffic patterns to reduce CO2 emissions in urban planning (Chen, *et al*., 2023), and serve as generally effective tools for managing and predicting CO2 emissions across various industries.

Table II. List of selected articles for review

Article ID	Title	Database (S/W)	Reference	Journal	Score out of 5
A1	Research on a carbon emission calculation model and method for an underground fully mechanised mining process	S	Li, B. *et al*., 2022. Research on a Carbon Emission Calculation Model and Method for an Underground Fully Mechanised Mining Process. MDPI, Energies, Volume 15, Issue 8.	Energies	**4**
A2	Modelling of heat and carbon monoxide emitted from moving cars in an underground car park	S	Xue, H. & Ho, J. C., 2000. Modelling of Heat and Carbon Monoxide Emitted from Moving Cars in an Underground Car Park. Tunnelling and Underground Space Technology, 15(1), pp. 101-115.	Tunnelling and Underground Space Technology	**4**
A3	A calculation model of carbon emissions based on multi-scenario simulation analysis of electricity consumption	S, W	Chen, X. *et al*., 2022. A Calculation Model of Carbon Emissions Based on Multi-Scenario Simulation Analysis of Electricity Consumption. MDPI, Sustainability 14(14), p. 8765.	Sustainability	**4**
A4	Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency	S, W	Sun, W. & Huang, C., 2022. Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency. Journal of Cleaner Production, Volume 338.	Journal of Cleaner Production	**3**
A5	Modelling carbon dioxide emissions with a system of differential equations	S	Tsokos, C. P. & Xu, Y., 2009. Modelling carbon dioxide emissions with a system of differential equations. Nonlinear Analysis: Theory, Methods & Applications, Volume 71, Issue 12, pp. e1182-e1197.	Nonlinear Analysis	**4**

A6	Quantitative evaluation of carbon emissions with mining technology development: a case study of an iron mine in China	S, W	Yao, N. *et al*., 2023. Quantitative evaluation of carbon emissions with mining technology development: a case study of an iron mine in China. Environmental Science and Pollution Research 30, p. 97673–97687.	Environmental Science and Pollution Research	**4**
A7	Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines	S, W	Ren, G. *et al*., 2023. Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines. Sustainability, Volume 15, p. 12738.	Sustainability	**4**
A8	Modelling traffic air pollution in road tunnels	S, W	Bellasio, R., 1997. Modelling traffic air pollution in road tunnels. Elsevier, Atmospheric Environment Vol. 31, No. 10.	Atmospheric Environment	**4**
A9	Spatial and temporal analysis of influential factors on motor vehicle carbon monoxide emissions in China considering emissions trading scheme	S, W	Zhao, S., Liu, L. & Zhao, P., 2024. Spatial and temporal analysis of influential factors on motor vehicle carbon monoxide emissions in China considering emissions trading scheme. Environmental Science and Pollution Research, Volume 31, pp. 9811-9830.	Environmental Science and Pollution Research	**5**
A10	Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors	S, W	Katta, A. K., Davis, M. & Kumar, A., 2019. Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors. Journal of Cleaner Production, 245(2020), p. 118718.	Journal of Cleaner Production	**2**
A11	GIS-Based Approach to Spatio-Temporal Interpolation of Atmospheric CO2 Concentrations in Limited Monitoring Dataset	S, W	Bezyk, Y., Sówka, I., Górka, M. & Blachowski, J., 2021. GIS-Based Approach to Spatio-Temporal Interpolation of Atmospheric CO2 Concentrations in Limited Monitoring Dataset. Atmosphere, Volume 12, p. 384.	Atmosphere	**4**

During the investigation of error assessment methods used in carbon and spatial models, the author identified that the following tests and models were widely employed:

a. Greenhouse Gas Emissions Accounting Methodology and Reporting Guide for China’s Coal Producers to compare the B-R model results
b. IPCC method to compare the B-R model results
c. Regression analysis, using the R software and the GTWR regression model to determine the standard error
d. Mean absolute percentage error (MAPE) and root mean square error (RMSE)
e. Relative error to compare the theoretical calculation and the actual energy consumption
f. Comparing the reported NRCan data and LEAPCANMIN model
g. Kriging error predictions

The China Development and Reform Commission commissioned the Greenhouse Gas Emissions Accounting Methodology and Reporting Guide for China's coal producers. For model validation, the second technique identified was the IPCC method, a global carbon accounting model developed by the Intergovernmental Panel on Climate Change (IPCC). Additionally, regression analysis is commonly used for model validation, as it helps quantify the uncertainty in projected values through the calculated standard error. Research studies identified this as the third method for validating the models. MAPE and RMSE, commonly used forecasting key performance indicators (Sun & Huang, 2022),were identified as the fourth error assessment method. The fifth method involved measuring relative error as the difference between theoretical and actual energy consumption. In another study, error assessment was conducted by comparing LEAPCANMIN model output data with reported mining data for carbon emissions in the iron, gold, and potash sectors. The final technique employed the kriging method to optimise interpolation results in a spatial model of atmospheric CO_2 concentrations.

When assessing the dataset types used in model formulation, the author discovered that real historical data was utilised in ten articles; however, none of the models included actual readings of carbon emissions from underground environments. Instead, the data primarily came from national databases. The studies reviewed employ diverse methodologies to gather and analyse carbon emissions data. The first study focuses on carbon emissions in the Fifth-II mining area of Jinda coal mine in Tengzhou City. The second study simplifies model development by using data from a small-scale car park, with assumptions for heat and CO emissions based on existing literature rather than historical data. In the third study, energy consumption data from G province between 2010 and 2020 is utilised. The fourth study draws on panel data from 2000 to 2016, sourced from the China Statistical Yearbook and Energy Statistical Yearbook.

The fifth study uses historical annual data from the Carbon Dioxide Information Analysis Centre covering the period from 1950 to 2005 for the continental United States. Another study assesses the carbon emission impact of underground metal mines using data from the largest underground iron mine in Anhui Province, China. A subsequent study uses a gold-copper mine as a case study to predict emissions with a proposed model.

Further, data from 34 vehicles, categorised by fuel type, age, engine cylinder capacity, and weight, is used in another study. Another study collects sample data from 1980 to 2021 across 31 Chinese provinces, sourced from the China Mobile Source Environmental Management Annual Report, China Statistical Yearbook, and China Transportation Statistical Yearbook. The tenth study gathers data on the iron, gold, and potash mining sectors from the SEDAR database, covering 102 mine sites in Canada. Lastly, seasonal variability of atmospheric CO_2 was directly measured in Wroclaw, Poland, from July 2017 to August 2018.

To validate these emission models, techniques such as the China Coal Production Enterprises Greenhouse Gas Emissions Accounting Methodology and Reporting Guide, along with the IPCC method, have been employed. A study employing these popular methods resulted in the creation of the B-R model, a unique approach for calculating carbon emissions. In a different study, the validity and comparative experiments verified the validity and robustness of the proposed carbon emission intensity model. When using differential equations to model emissions, the authors in one study use three different statistical procedures, namely R2 (R2 adjusted), PRESS statistic, and residual analysis to evaluate the quality of the proposed differential methods. In a separate study, the calculation results are compared with the actual energy consumption data of the mine to validate the proposed model. Another study modelling traffic air pollution, a sensitivity analysis is conducted to verify the model outputs to different input parameters. Further analysis shows the use of R2, adjusted R2 and AICc as assessment criteria to evaluate the model's accuracy for a study on spatial and temporal analysis. In a different study, the differences between model-calculated and historical energy demand and GHG emissions serves as the validation technique. Finally, cross-validation was employed in a study that uses GIS approaches to interpolate for limited datasets of atmospheric CO2 concentrations.

The review of the articles on carbon emission sources used in the models reveals two main categories: direct and indirect emissions. Table 3 provides a summary of the direct and indirect carbon sources as well as the carbon-producing processes found in the literature. The list is as follows:

i. Falling and mining coal, transporting coal, roof support, treatment of the coal mine gob area

ii. Preparation, operation, and final stage
iii. Fuel combustion, torch combustion, and GHG fugitive
iv. Production of consumed materials, fuel, and electricity, fuel combustion and explosive explosions
v. Vehicle emissions
vi. Economic level, population size, road mileage intensity, motor vehicle intensity, and metro line intensity
vii. GDP, population i.e., indirect variables
viii. Gas fuels, solid fuels, liquid fuels, gas flares, cement, bunker

In summary, the studies analysed prove that the modelling environment plays a critical role in determining the carbon modelling methods used. Accurately identifying both direct and indirect sources of carbon emissions is essential, particularly in studies focused on underground mines. By analysing the specific components and techniques of mining operations, total carbon emissions can be more precisely quantified. However, a review of existing literature reveals a significant gap: only 27% of the examined studies, or just three out of eleven, specifically address carbon emissions from underground mining processes. Additionally, while these studies highlight the relevance of linking indirect sources of emissions to macroeconomic policy decisions, they fall short of providing comprehensive and actionable insights for reducing emissions in underground mining. This emphasises the pressing need for more focused research on carbon emission models tailored to underground mining environments.

Table III. Carbon emission sources of coal mines, (Li, et al., *2022)*

Direct Emissions		
Process Linkage	**Type of Source**	**Main Greenhouse Gases**
Diesel, gasoline, and other fuels for equipment power	Emergency power generation equipment, mine transportation, etc.	CO_2, N_2O, CH_4
Production system	Spontaneous combustion caused by stacking of coal gangue and raw coal Vaporize	CO_2, N_2O, CH_4, H_2S
Transportation system	Transportation in the mine Staff transportation	CO_2, N_2O, CH_4
Subsidiary production system	Fossil raw coal used in staff bathhouse	CO_2, N_2O, CH_4
Indirect emissions		
Process linkage	Type of source	Main greenhouse gases
Production system	Coal mining process related to the use of machine power (specifically, purchased power)	CO_2, N_2O, CH_4
Auxiliary production systems	Drainage system, ventilation system, gas emissions, and other power use (specifically, purchased power)	CO_2, N_2O, CH_4
Subsidiary production systems	Transmission and distribution processes Personnel and building consumption	CO_2, N_2O

Analysis of trends and methods
In this section, the author explores various notable trends and methodologies in the literature on carbon emission modelling, indicating a transition towards more advanced strategies for forecasting, calculating, and measuring carbon emissions. The models outlined in the paper are primarily classified into two categories: Traditional Data Models and Machine Learning Models, each employing unique approaches for estimating carbon emissions. Table 4 provides a summary of this analysis.

In traditional data models the IPCC method is a significant model within this category, especially in mining applications. For example, and as the author discusses in the literature review expansion section, (Li, *et al.*, 2022) formulated the B-R model for carbon emission assessment in fully automated underground mining operations. The B-R model has been effectively applied at the Jinda coal mine, showcasing its capability in quantifying emissions from particular mining operations, including coal extraction, transportation, and roof support.

Machine learning approaches typically excel with large and complex datasets, offering increased accuracy in emissions prediction. Artificial neural networks are especially effective for forecasting in energy and environmental systems, as evidenced by (Niu, *et al.*, 2020), who illustrated their usefulness in predicting carbon emissions in China. On the other hand, Grey Forecasting Models, frequently used in systems with uncertain variables, are distinguished by their accuracy in situations where data is limited or inconsistent. These models are applied in different industries, including the energy sector, where (Liu, *et al.*, 2014) merged ARIMA with grey forecasting to simulate energy patterns in the thermal power industry. These hybrid models demonstrate an increasing trend of mixing classic statistical methods and machine learning to improve prediction ability.

Table IV. Analysis of carbon emission model trends

Type of carbon emission modelling	*Trend and methods*
Traditional Data Models	Indirect Variables - LMDI Decomposition Model, STRIPAT Model, Autoregressive Distributed Lag Model, IPCC Method
Machine Learning Models	Time Series Models: Moving Average, Autoregressive, and ARIMA, Grey Forecasting Models, Artificial Neutral Networks
Monte Carlo Simulations	CO_2 sequestration
Differential Equation Models	CO_2 emission predictions/forecasting
Hybrid Models	Bottom-up and top-down approaches

Monte Carlo methods provide a strategy that is often used in carbon sequestration and high-uncertainty systems. Studies by (Kumar, *et al*., 2011) and (Jai-Yong, *et al.*, 2018) demonstrate the value of Monte Carlo simulations in situations where random variables are prevalent in the system. Specifically, grid-based Monte Carlo simulations have been employed to assess carbon sequestration capacity, as shown in geological carbon storage research. These methodologies allow researchers to conduct numerous simulations to forecast the possibility of several different outcomes, making them suitable for studies related to underground mining environments, where (Takashi & Kozo, 2011) applied Monte Carlo techniques to improve well placement for CO_2 sequestration.

In addition, differential equation models have significantly contributed to forecasting carbon emissions. For example, and as the author discusses in the literature review expansion section, (Tsokos & Xu, 2009) formulated a set of differential equations for various carbon emission sources, including gaseous and liquid fuels, bunker fuels, and cement production. This model helps with short- and long-term emission forecasts and has been validated with historical data from the U.S. spanning over five decades. Likewise, (Han, *et al*., 2022) used a two-dimensional differential equation model to predict China's timeline for reaching carbon neutrality.

Another notable trend is the combined use of multiple models to generate stronger results. (Wang & Lin, 2017) example, used the STIRPAT model together with vector autoregressive models to accurately predict carbon emissions in China's business sector. This hybrid approach exemplifies the growing trend of integrating different methods to overcome the limitations of single models. In carbon footprint studies, combining bottom-up and top-down methodologies, such as the EIO method, provides a comprehensive perspective of emissions that takes into account both direct and indirect variables (Pandey, *et al.*, 2011).

This analysis revealed that, in order to increase forecast accuracy and address the complex, multi-dimensional nature of carbon emissions, carbon emission modelling is moving towards the combined use of cutting-edge computational techniques with conventional models.

Discussion of results

Real-world applications

The author's conclusions from the literature point to practical ideas that have the potential to have significant impacts on the mining sector. The B-R model, for example, can help mining professionals pinpoint precise carbon emission sources at various operational phases. Businesses can track fuel consumption, energy use, and fugitive gas emissions by using this model, which enables them to optimise their operations to reduce carbon emissions. In addition, emission trends can be predicted using machine learning models like ARIMA and ANN, which makes it possible to apply more proactive and flexible carbon management techniques.

The models in the literature further demonstrate the significance of including both direct and indirect variables to fully capture all the factors contributing to carbon emissions. For instance, scenario analyses that assist in forecasting emissions and guiding regulatory compliance factor in variables such as GDP, population growth, and energy use intensity—all of which are frequently used in STIRPAT models. Finally, the literature also highlights how Monte Carlo simulations help mining companies study various carbon reduction strategies in complex underground environments by addressing data uncertainties.

Gaps in the research

While carbon emission models for underground mining have advanced significantly, there are several research gaps that need to be filled. These gaps mostly relate to improving model scalability and accuracy in increasingly complex mining environments, combining new regulatory frameworks, and modifying current models to new technologies.

The integration of new technologies like artificial intelligence (AI), the Internet of Things (IoT), and autonomous mining systems is not fully accounted for by many existing models. These technologies have the potential to significantly increase the accuracy of carbon emission models by providing real-time automation and data collection. To improve prediction accuracy and intentional emissions control, more research is required to modify current models, taking into account real-time monitoring systems which could allow dynamic modifications in response to changing mining conditions.

Models that can adapt to changing legal requirements are becoming increasingly important as the focus shifts to stricter environmental regulations, particularly in South Africa where carbon emission policy is evolving. Future research should focus on creating adaptable models that can take new compliance requirements, changing carbon tax rates, and updated emissions reporting standards into account.

While indirect emissions, are still largely unstudied, many current models concentrate on direct emissions from fuel combustion and energy use. Improving models to better capture and quantify these indirect emissions which can account for a sizable amount of the total carbon footprint in underground mining operations should be a key focus area for future research.

The availability and quality of data is a persistent challenge in the modelling of carbon emissions, particularly in underground mining environments. Often, models are validated using historical data, which might not be the most accurate representation of current or future operational conditions. Furthermore, model accuracy may be limited by variations in data collection techniques used across various mining operations. Future research should explore more effective ways to standardise data gathering and provide real-time monitoring underground. A more practical solution could involve combining AI-powered sensors with IoT devices to provide constant data streams for model validation and calibration.

Many carbon emission models, especially those that are specific to a region, have difficulty scaling across various geological settings and mining methods. To make flexible models more relevant and widely applicable across diverse mining environments, more research is needed to develop models that can be used in both large- and small-scale underground mines.

CONCLUSION

Eleven articles met the criteria for the systematic literature review, addressing five research questions based on studies published between 1994 and 2024. The main conclusions of the research review are that during the studied period only 27% of publications on carbon emission models from the selected databases specifically focused on underground carbon emission models. The systematic review examined carbon emission models developed for underground environments in terms of the type of dataset that was used, the carbon emitting sources considered in the model, as well as the methods used to assess for error and consequently validate the model.

The identified carbon accounting model and carbon emissions calculation model of underground metal mines were developed primarily based on direct and indirect carbon sources. The IPCC was found to be helpful in validating the carbon accounting model, but as carbon accounting and carbon modelling employ different methodologies, it would not be appropriate for a carbon emission model. Moreover, although the carbon emissions calculation model of underground metal mines was directly relevant to the review's goal, it lacked a method for demonstrating how the model was validated and then applied to forecast emissions in the future.

Moreover, none of the 11 studies identified for analysis included a carbon emission model based on actual or observed emissions within an underground environment. This significant gap in the literature emphasises the urgent need for a framework specifically designed to address carbon emissions in underground mining. The absence of real-world data in existing models limits their predictive accuracy and practical application in reducing emissions. As a result, this paper highlights the critical necessity of developing a robust framework that not only fills this void in research but also enables the creation of predictive carbon emission models for underground metal mines. This framework would be instrumental in providing a spatial model for comprehensive visual analysis, paving the way for more effective strategies to mitigate carbon emissions in these challenging environments.

ACKNOWLEDGEMENTS

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APPENDIX I

		Carbon emission models	GHG emission models	CO2 emission models	U/G emission modelling	U/G GHG modelling	U/G CO2 modelling
First Filter	Scopus	67 055	7 071	28 432	446	18	550
	Web of Science	70 326	8 151	41 419	1 396	37	1 140
Second Filter	Scopus	47 003	5 621	21 132	337	15	411
	Web of Science	39 893	5 619	25 802	564	26	641
Third Filter	Scopus	46 401	5 621	20 597	336	15	407
	Web of Science	39 742	5 619	25 713	558	26	640
Fourth Filter	Scopus	46 401	5 617	20 597	336	15	407
	Web of Science	39 742	5 619	25 713	558	26	640

APPENDIX II

List for Selection Criteria:

1. Does the research discuss carbon or GHG emissions in a surface or underground environment	Y/N
2. Are carbon or GHG emissions modelled quantitatively/qualitatively	Y/N
3. Is there a spatial model of the emissions	Y/N
4. Have the direct and/or indirect sources/factors of the emission been identified and listed	Y/N
5. Does the study use a specific dataset to create the model	Y/N

APPENDIX III

Article ID	**Title**	**Score out of 5**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**
A1	Research on a carbon emission calculation model and method for an underground fully mechanised mining process	**4**	Y	Y	N	Y	Y
A2	Modelling of heat and carbon monoxide emitted from moving cars in an underground car park	**4**	Y	Y	Y	Y	N
A3	A calculation model of carbon emissions based on multi-scenario simulation analysis of electricity consumption	**4**	Y	Y	N	Y	Y

A4	Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency	**3**	N	N	Y	Y	Y
A5	Modelling carbon dioxide emissions with a system of differential equations	**4**	Y	Y	N	Y	Y
A6	Quantitative evaluation of carbon emissions with mining technology development: a case study of an iron mine in China	**4**	Y	Y	N	Y	Y
A7	Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines	**4**	Y	Y	N	Y	Y
A8	Modelling traffic air pollution in road tunnels	**4**	Y	Y	N	Y	Y
A9	Spatial and temporal analysis of influential factors on motor vehicle carbon monoxide emissions in China considering emissions trading scheme	**5**	Y	Y	Y	Y	Y
A10	Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors	**2**	Y	N	N	N	Y
A11	GIS-based Approach to Spatio-Temporal Interpolation of Atmospheric CO2 Concentrations in Limited Monitoring Dataset	**4**	Y	N	Y	Y	Y

REFERENCES

Adebayo, T. S., Uhunamure, S. . E. & Shale, K., 2023. A time-varying approach to the nexus between environmental related technologies, renewable energy consumption and environmental sustainability in South Africa. *Scientific Research 13(14860).*

Agbajor, F. D., Mewomo, M. C., Umoh, V. B. & Makanjuola, S. A., 2023. Building energy management system research in South Africa—A decade overview. *Energy Reports 9,* pp. 33-39.

Ayompe, L. M., Davis , S. J. & Egoh, B. N., 2021. Trends and drivers of African fossil fuel CO2 emissions 1990–2017. *Environmental Research Letters, Volume 15, Number 12.*

Bezyk, Y., Sówka, I., Górka, M. & Blachowski, J., 2021. GIS-Based Approach to Spatio-Temporal Interpolation of Atmospheric CO2 Concentrations in Limited Monitoring Dataset. *Atmosphere,* Volume 12, p. 384.

Bugarski, A. D. & Hummer, J. A., 2020. Contribution of various types and categories of diesel-powered vehicles to aerosols in an underground mine. *Journal of Occupational and Environmental Hygiene,* 17(4), pp. 121-134.

Chen, Xiaoli; Liao, Zhiwei; Gao, Zhihua; Li, Qian; Lv, Peng; Zheng, Guangyu; Yang, Kun., 2022. A Calculation Model of Carbon Emissions Based on Multi-Scenario Simulation Analysis of Electricity Consumption. *MDPI, Sustainability 14(14),* p. 8765.

Chen, Xiao; Tao, Tao; Zhou, Jiaxin; Yu, Helong; Guo, Hongliang; Chen, Hongbing., 2023. Simulation and Prediction of Greenhouse Gas Emissions from Beef Cattle. *Sustainability,* 15(15), p. 11994.

Donald, P., Mayengo, M. & Lambura, A. G., 2024. Mathematical modeling of vehicle carbon dioxide emissions. *Heliyon,* Volume 10.

Han, L., Sui, H. & Ding, Y., 2022. Mathematical Modeling and Stability Analysis of a Delayed Carbon Absorption-Emission Model Associated with China's Adjustment of Industrial Structure. *Mathematics,* 10(17), p. 3089.

Hofmeyer, C. D., 2019. *The impact of carbon regulation on the mining industry.* [Online] Available at: https://www.cliffedekkerhofmeyr.com/export/sites/cdh/en/news/publications/2019/Corporate/downloads/Mining-and-Minerals-Alert-6-February-2019.pdf

Jai-Yong, Park; Sungho, Lee; Jung-Hwi, Kihm; Jun-Mo, Kim; Lee, Il Yong., 2018. Probabilistic evaluation of multi-fluid-phase carbon dioxide storage capacities of saline formations in the Pohang Basin, Korea using three-dimensional geologic modeling and grid-based Monte Carlo simulation. *International Journal of Greenhouse Gas Control, Volume 79,* pp. 289-312.

Katta, A. K., Davis, M. & Kumar, A., 2019. Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors. *Journal of Cleaner Production,* 245(2020), p. 118718.

Kohmuean, P., Inthomya, W. & Wongkoblap, A., 2021. Monte Carlo Simulation and Experimental Studies of CO2, CH4 and Their Mixture Capture in Porous Carbons. *Molecules, 26(9),* p. 2413.

Kopac, D., Hus, M., Ogrizek, M. & Likozar, B., 2017. Kinetic Monte Carlo Simulations of Methanol Synthesis from Carbon Dioxide and Hydrogen on Cu(111) Catalysts: Statistical Uncertainty Study. *he Journal of Physical Chemistry,* pp. 17941-17949.

Kumar, R., Li, Z. & Levin, A. D., 2011. Modeling of carbon dioxide condensation in the high pressure flows using the statistical BGK approach. *Physics of Fluids 23.*

Li, B.; Shi, Y.; Hao, J.; Ma, C.; Pang, C.; Yang, H., 2022. Research on a Carbon Emission Calculation Model and Method for an Underground Fully Mechanized Mining Process. *MDPI, Energies, Volume 15, Issue 8.*

Li, Xudong; Zhou, Wei; Liu, Zixuan; Li, Haowei; Lu, Jing., 2021. *Research Overview on Carbon Emission Models.* Online, IEEE.

Liang, W., Zhao, B., Liu, J. & Pei, J., 2020. Can carbon dioxide be a good indicator for formaldehyde in residences?—Monte Carlo modeling for a whole year. *Science and Technology for the Built Environment,* pp. 749-762.

Liu, L., Zhao, E., Chen, C. & Wang, J., 2014. Can China realize its carbon emission reduction goal in 2020: From the perspective of thermal power development. *Applied Energy, Volume 124, ,* pp. 199-212.

Mahboob, M. A., Celik, T. & Genc, B., 2022. Review of machine learning-based Mineral Resource estimation. *SAIMMN,* pp. 655-664.

McDonough, L.K Iverach; Beckmann, S.; Manefield, M.; Rau, G.C; Baker, A; Kelly, B.F.J., 2016. Spatial variability of cave-air carbon dioxide and methane concentrations and isotopic compositions in a semi-arid karst environment. *SpringerLink, Environmental Earth Sciences 75, Article number 700.*

McSweeney, R. & Timperley, J., 2018. *The Carbon Brief Profile: South Africa.* [Online] Available at: https://www.carbonbrief.org/the-carbon-brief-profile-south-africa/

Niu, Dongxiao; Wang, Keke; Wu, Jing; Sun, Lijie; Liang, Yi; Xu, Xiaomin; Yang, Xiaolong., 2020. Can China achieve its 2030 carbon emissions commitment? Scenario analysis based on an improved general regression neural network. *Journal of Cleaner Production, Volume 243.*

Padhan, L. & Bhat, S., 2023. Interrelationship between trade and environment: a bibliometric analysis of published articles from the last two decades. *Environmental Science and Pollution Research 30,* p. :17051–17075.

Pandey, D., Agrawal, M. & Pandey, J., 2011. Carbon footprint: current methods of estimation. *SpringerLink, Environmental Monitoring and Assessment 178 ,* pp. 135-160.

Pfaff, R., 2023. Braking distance prediction for vehicle consist in low-speed on-sight operation: a Monte Carlo approach. *Railway Engineering Science, Volume 31,* pp. 135-144.

Ren, Gaofeng; Wang, Wei; Wu, Wenbo; Hu, Yong; Liu, Yang., 2023. Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines. *Sustainability,* Volume 15, p. 12738.

Statista, 2022. *Statista, Energy & Environment, Emissions.* [Online] Available at: https://www.statista.com/statistics/486073/co2-emissions-south-africa-fossil-fuel-and-industrial-purposes/

Sun , W. & Huang, C., 2022. Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency. *Journal of Cleaner Production, Volume 338.*

Takashi, G. & Kozo, S., 2011. Optimization of well placement for geological sequestration of carbon dioxide using adaptive evolutionary Monte Carlo algorithm. *Energy Procwdia, Volume 4,* pp. 4275-4282.

Tsiakmakis Stefanos; Ciuffo Biagio; Marotta Alessandro; Fontaras Georgio; Anagnostopoulos Konstantinos; Arcidiacono Vincenzo; Praksova Renata., 2016. Introducing a New Emissions Certification Procedure for European Light-Duty Vehicles: Monte Carlo Simulation of the Potential Effect on Fleet Carbon Dioxide Emissions. *Transportation Research Record, 2572(1),* pp. 66-77.

Tsokos, C. P. & Xu, Y., 2009. Modeling carbon dioxide emissions with a system of differential equations. *Nonlinear Analysis: Theory, Methods & Applications, Volume 71, Issue 12,* pp. e1182-e1197.

Wang, A. & Lin, B., 2017. Assessing CO2 emissions in China's commercial sector: Determinants and reduction strategies. *Journal of Cleaner Production, Volume 164,* pp. 1542-1552.

Wasik, O Dominika; Martin-Calvo Ana; Gutierrez-Sevillano, Jose Juan; Dubbeldam David; Vlugt, J.H Thijs; Calero Sofia., 2023. Enhancement of formic acid production from carbon dioxide hydrogenation using metal-organic frameworks: Monte Carlo simulation study. *Chemical Engineering, Volume 467,* p. 143432.

Wu, Yuzhe; Shen, Jiahui; Zhang, Xiaoling; Skitmore, Martin; Lu, Wisheng., 2016. The impact of urbanization on carbon emissions in developing countries: a Chinese study based on the U-Kaya method. *Journal of Cleaner Production, Volume 135,* pp. 589-603.

Xiao, X. & Duan, H., 2020. A new grey model for traffic flow mechanics. *Engineering Applications of Artificial Intelligence,* Volume 88, p. 103350.

Xue, H. & Ho, J. C., 2000. Modelling of Heat and Carbon Monoxide Emitted from Moving Cars in an Underground Car Park. *Tunnelling and Underground Space Technology,* 15(1), pp. 101-115.

Yang, R.-j., Ding, D.-f. & Yan, F., 2019. *Application of K-Nearest Neighbor Algorithm in Determination of Air Quality*. Guangzhou, China, Association for Computing Machinery, pp. 108-112.

Yao, N. et al., 2023. Quantitative evaluation of carbon emissions with mining technology development: a case study of an iron mine in China. *Environmental Science and Pollution Research 30,* p. 97673–97687.

Yoro, K. O. & Sekoai, P. T., 2016. The Potential of CO2 Capture and Storage Technology in South Africa's Coal-Fired Thermal Power Plants. *MDPI, Environments, Volume 3.*

Yu-Chia Ko, K. Z. Y.-L. L., 2021. Carbon capture and storage in South Africa: A technological innovation system with a political economy focus. *Technological Forecasting and Social Change, Volume 166.*

Zhang, Z., Hong, W.-C. & Li, J., 2020. Electric Load Forecasting by Hybrid Self-Recurrent Support Vector Regression Model With Variational Mode Decomposition and Improved Cuckoo Search Algorithm. *IEEE Access, Volume 8,* pp. 14642 - 14658.

Zhao, S., Liu, L. & Zhao, P., 2024. Spatial and temporal analysis of infuential factors on motor vehicle carbon monoxide emissions in China considering emissions trading scheme. *Environmental Science and Pollution Research,* Volume 31, pp. 9811-9830.

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The role of voluntary sustainability standards for mineral raw materials in catalysing responsible mining practices: Case study of IRMA implementation at Anglo American Platinum

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Anglo American Platinum has committed to having all its operations undergo third-party audits against responsible mine certification systems, namely the Initiative for Responsible Mining Assurance (IRMA) by 2025. This commitment was in response to growing stakeholder demand for traceability and provenance.

This paper explores and aims to provide a nuanced perspective of the implementation of this responsible mining audit across its platinum-group metals (PGM) operations, including lessons learned and challenges experienced using a case study approach involving three mining sites. These sites are acknowledged in their various capacities as: the first site globally to undergo this audit, the first PGM mine in South Africa to implement the audit, as well as the first mine globally to conduct a surveillance audit.

In our experience multi-stakeholder initiatives (in this case IRMA) foster increased stakeholder engagement, which can build trust. It has fostered trust and credibility with customers through increased visibility and traceability of the mineral value chain and has improved on-site practices. Audits however are not a silver bullet and have their limitations, including that they are limited in time and scope. Additionally, summarising inputs and performance into a score does not always account for the unique operating contexts. The role of these audits cannot be undermined in their ability to improve performance; however for this performance to be sustainable and credible, a functioning rule of law is required.

Keywords: responsible mining, stakeholders, audits, standards, supply chain, sustainability, risk management

*initiatives, standards and schemes used interchangeably throughout the paper

INTRODUCTION

The most widely adopted and used definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987). This definition implores us to consider the effects of our behaviours and their related impacts both in the present and in future. Minerals and metals have long played a key role in "underpinning the prosperity of current and future civilizations" (Giurco and Cooper, 2012) placing them at the centre of modern living. The mining industry therefore plays a significant role in ensuring an acceptable quality of life (Moran *et al*., 2014), occupying a primary role in the beginning of a resource supply chain (ICMM, 2012).

However, while the role of mining can be argued as being indispensable to modern life, it is plagued by its impacts on natural environments and societies. The impact of mining, regardless of where it occurs, will result in environmental and social change ranging from habitat loss in the physical environment to – and not limited to – cultural change for nearby or host communities (Miranda *et al*., 2005). The mining industry is further associated with unfair working conditions, poor relationships with surrounding communities and bad mine closure practices that leave the communities with long- standing problems (Goodland, 2012).

Examples of the negative impact of mining found in news headlines that dominated media in recent years include compensation by Vale for the Brazil dam collapse that killed 272 people (CNN, 2021), loss of heritage through Rio Tinto blasting of a 46 000 year old Aboriginal site (The Guardian, 2020b) among several others (BBC, 2021; The Guardian, 2020a, 2021; Wall Street Journal, 2020). These recent events continue to erode trust in the mining industry such that the industry cannot credibly self-certify its own sustainability performance. The negative news headlines have not gone unnoticed. Mining and metal companies acknowledge the importance of environmental and social credibility to the extent that it was identified as the biggest risk facing the mining sector in 2022 in an EY report (EY, 2021) The negative impact of mining companies has led the world to demand more transparency in mining value chains to ensure that metal products have been responsibly mined (Ali *et al*., 2015).

The acknowledgement of this has not been without change, from mining companies, regulators, civil society actors and consumers. The past two decades saw significant movement from the industry, spurring technological advancements and improved risk management; stricter regulations and civil society advocacy. To date however, legislation and existing frameworks have not been consistently and adequately applied to effectively mitigate some of these known negative impacts of mining; highlighting the need for an effective initiative/mechanism that will accelerate efficacy in the sustainable mining agenda beyond regulation (Miranda *et al*., 2005).

This paper seeks to unearth the lessons learnt during the implementation of mining standards as a mechanism that goes beyond regulation to highlight responsible mining practices. It begins with analysing the role of mining standards as a means of understanding sustainability credentials of mined products, followed by a review of the evolution of mining standards and current debates around them. It then considers a case study of the implementation of the Initiative for Responsible Mining Assurance (IRMA) responsible mining standard at Anglo American Platinum (AAP) operations, detailing key lessons learned through implementing these. It concludes with an analysis of the extent to which participation in this has catalysed responsible mining at a site level and the possibilities of this, for the industry and mineral-rich countries at large.

The use of mining standards as a responsible sourcing mechanism

The negative news headlines have not gone unnoticed and there is increasing scrutiny on sustainability performance. One way sustainability performance is being analysed is through responsible sourcing mechanisms which interrogate how sustainability risks are being managed at the mines and across the mining value chain where mined materials are used (Bilham, 2021). Responsible sourcing mechanisms are growing in demand as they often provide external verification of the sustainability performance of the mining industry which has lost credibility in self-reporting (Franken & Schütte, 2022). There is growing pressure from governments and consumers on mining companies to focus on responsible sourcing mechanisms (Bilham, 2021; van den Brink *et al*., 2019). Responsible sourcing mechanisms include mining standards that set requirements and independent assurance mechanisms to check that minerals and metals have been extracted in a way that complies with leading sustainability practices (Gurzawska, 2020). Mining standards are sometimes called certification schemes or voluntary sustainability standards and are categorised as a form of private regulation (Ali *et al*., 2015; Eberlein *et al*., 2014). In this study, they will be referred to as responsible mining standards to simplify the language.

The evolution of mining standards

Responsible mining initiatives* and narratives have found their expression largely through voluntary sustainability standards (Di Capua *et al*., 2021). The United Nations Forum on Sustainability Standards defines voluntary sustainability standards as "standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics including respect for basic human rights, worker health and safety, environmental impacts of production, community relations, land use planning and others" (Axel *et al*., 2022). These are seen as a market-led approach to promoting sustainable production and business practice (Komives and Jackson, 2014). Over the years, there has been a proliferation of voluntary sustainability standards varying to differing degrees and focusing on various aspects i.e., topic-specific, single-issue, multi-issue, commodity-specific, industry-led etc. Currently, the number of existing voluntary sustainability standards across several sectors ranges between 300 and 500 (Marx *et al.,* 2022).

The International Council on Mining and Metals (ICMM) is the longest-serving sustainability scheme and the one to which most major multinational companies have subscribed. Following its development in 2001, the Mining Association of Canada (MAC) initiated Towards Sustainable Mining (TSM) in 2004. TSM is currently adopted by nine countries, representing 26% of the global mineral and metal production value (Gudrun and Schutte, 2022). These are not an exhaustive list of sustainability standards for mining as they range from commodity specific to those that assure the entire supply chain or limited parts. Figure 1 illustrates sustainability schemes applicable to mining and processing only (Bilham, 2021), Di Capua *et al.,* 2021).

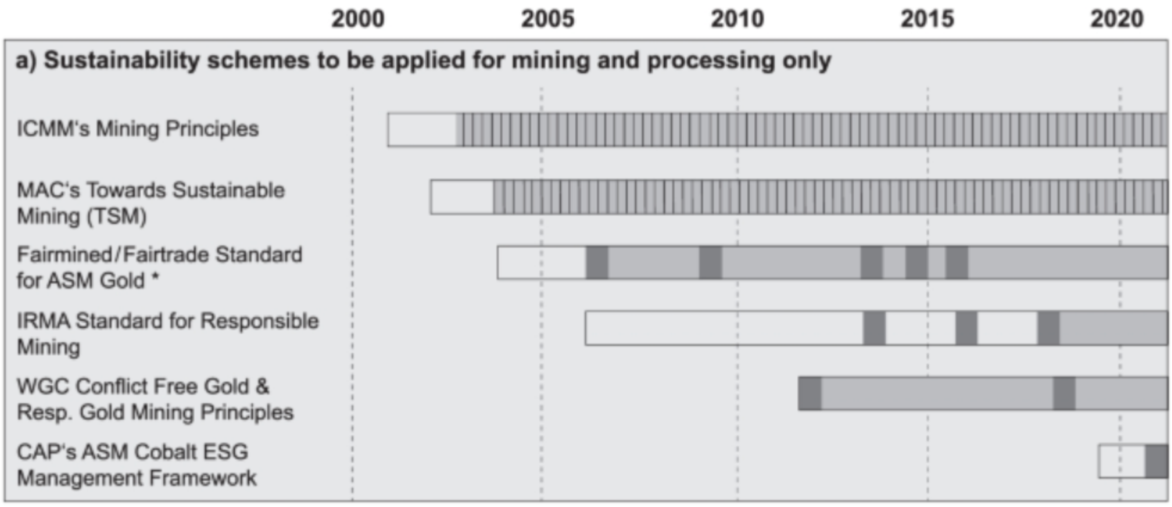

Figure 1. Sustainability schemes applicable to mining and processing only (Franken and Schutte, 2022).

As these schemes continue to increase in uptake, so too does the critique and scrutiny over their effectiveness, stimulating various actors to define the tenets of credible standards. The increase in the number of standards themselves has also brought complexity and reduced recognition of schemes in the market by different stakeholders such as customers, civil society and regulators (Heinz *et al.*, 2022; Human Rights Watch, 2022). They are critiqued mainly for lacking a comprehensive basis for environmentally and socially responsible mining standards (Miranda *et al*., 2005). Given that most of these are industry-led, they are also heavily criticised for their skewed power imbalance, with the rich and knowledgeable mining companies and impacted people unprotected by weak governance, thereby skewing the power to favour and serve companies. The best practice responsible mining standards will be seen as those that seek to redress this imbalance (Goodland, 2012) .

The emergence of multi-stakeholder sustainability standards reflects the changing role of mining and the need for social acceptance that extends beyond self-regulation by the mining company involved. Multi-stakeholder initiatives are found to be a "transnational private regulation", independent of government regulation but also not industry regulation and therefore a more direct approach to driving change in the mining industry (Sauer and Hiete, 2019). Miranda (2012) argues that a debate that is controlled by one sector is unlikely to produce meaningful results; rather this must be debated by a range of affected constituents (Miranda *et al*., 2005). This too is the case for responsible mining standards. IRMA is a responsible mining standard leading the redressing of the imbalance through its multi-stakeholder governance model (IRMA, 2023) and is to date seen as the most rigorous mining standard available (Lead the Charge, 2024, Murguia and Bastida, 2024).

Mining standards play a significant role in increasing transparency in mineral value chains and a clear example of this is the role that both the Kimberley Process and the Responsible Jewellery Council played in increasing transparency in the provenance of diamonds more than 20 years ago (Kimberley Process, 2023). This was followed by cross-commodity schemes like the mineral certification for the International Conference of the Great Lakes Region that focused on responsibly sourced tin, tantalum, tungsten and gold from the Gold Lakes Region (C. Mori Junior *et al.*, 2015). Standards such as IRMA also seek to increase transparency across commodities by highlighting sustainability practices at a mine site level.

The issue of provenance is an increasing priority for mining companies and customers in the mining value chain; however this is not limited to just mining. Increasingly, consumers want to know where their food comes from and how their clothes are made – and in the case of mining: how the metals and minerals are mined. A study by McKinsey & Company (2024) revealed that supply chain transparency and responsible sourcing rank within the top three sustainability dimensions for battery materials, and the top four for other materials. Given this, it is now commendable and distinguishing for companies to subject their operations to independent scrutiny through responsible mining standards and an established, verifiable, audited chain of custodies for the minerals and metals they mine (Goodland, 2012).

Anglo American's response to demand for increased transparency

In response to increased demand for transparency in sustainability practices at a mine site level, AAP has committed to having all its operations undergo third-party audits against responsible mine certification systems, namely IRMA by 2025. IRMA caters for diverse stakeholder interests, given that it is a multi-stakeholder initiative and provides increased transparency that caters to growing stakeholder inquiries on traceability and provenance by publishing detailed reports and including affected stakeholder feedback in the audit process. Downstream value chain customers in automotive sectors and digital technologies sectors have also joined IRMA as members and actively advocate for its uptake upstream.

METHODOLOGY

This paper seeks to unearth the lessons learnt during the implementation of mining standards as a mechanism that goes beyond regulation to highlight responsible mining practises. This will be achieved using a case study research method that reviews three AAP mining operations that have undergone IRMA audits. According to Sekaran and Bougie (2013), a case study research method is appropriate when one seeks to examine a real-life situation from various angles and perspectives. In this case, the implementation of the IRMA standard will be analysed across three sites from different perspectives. Bryman and Bell (2011) also emphasise that a case study is appropriate when there is anticipation of an opportunity to learn. A simple framework for analysing the lessons learnt from the implementation of the IRMA standard is presented in Table .

Table 1. Lessons learnt framework for reviewing the AAP IRMA implementation case study

Lessons learnt theme	Targeted audience that can benefit
Implementation process learnings	These will be valuable for other mining companies considering similar audits.
Audit report findings	These will be beneficial for various stakeholders interested in the sustainability performance of mining sites.
Release of audit results	These will be useful for understanding the impact of audits on downstream companies.

To support this framework, a high-level description of how the IRMA standard is implemented is presented next, followed by the results against the framework proposed above.

How an IRMA audit is conducted and implemented at a site

The IRMA audit process follows a four-step process, centred on continuous improvement that begins with a self-assessment on an IRMA provided tool (mine measure) by the mine site electing to be audited under the IRMA standard. This is followed by a stage 1 desktop-based audit by the independent third-party auditor or certification body selected by the mine site. The output of this is an indication of whether the site is ready to progress to stage 2 or if there are significant concerns that the site may find it worthwhile to correct before proceeding to the next stage. When a site is ready to proceed, a stage 2 on-site audit aimed at field verification of performance, including engagement with the mine operation's stakeholders, is then conducted by the certification body. These stakeholders include employees as well as external stakeholders such as communities and local government representatives. Following the stage 2 audit, mine sites have the option to undergo a 12-month elective corrective action period to focus on non-conforming critical requirements. These corrective actions must be accepted by the certification body before proceeding. Based on the certification body feedback, the corrective action period may be concluded with an on-site verification audit to verify the efficacy and completeness of action plans. The final report must be published and made publicly available before the mine site can make any IRMA-related claims. There are four IRMA achievement levels with the lowest being IRMA transparency and increasing to IRMA 50, IRMA 75 and ultimately IRMA 100. This is then followed by a surveillance audit 18 months after the public report has been made public and a recertification audit every three years. (IRMA, 2022). This process is illustrated in Figure 2.

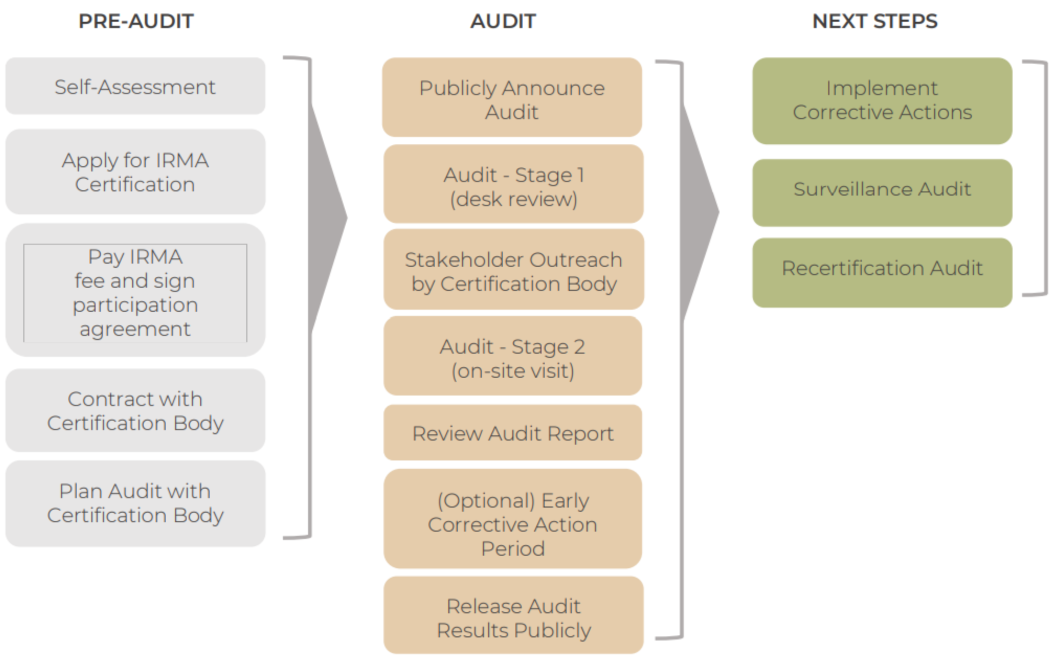

Figure 2. IRMA Independent Third-Party Assessment Process (IRMA, 2022).

Summary of IRMA audits implementation at AAP

This report will focus on the implementation of IRMA audits at three AAP operations listed below with audit completion date and IRMA achievement level reported for each site shown. At the time of writing this report there was a fourth audit underway at Mogalakwena mine but it has not been included in this study. All reports are publicly available at https://responsiblemining.net/.

- Unki mine achieved IRMA 75 in 2021
- Amandelbult mine achieved IRMA 50 in 2024
- Mototolo mine achieved IRMA 75 in 2024

While the IRMA standard is the same across all sites, these audits were undertaken during various periods, each with specific operating contexts and this highlights the complexities in applying universally defined principles in different specific contexts. For Unki, our platinum group metals (PGM) mine in Zimbabwe, this was the first IRMA audit in the world to be conducted with learning curves for the site, the auditors and even the IRMA standard team as well. Unki is also the first mine to complete an IRMA surveillance audit in addition to an initial audit. For Amandelbult and Mototolo, our South Africa-based PGM mines, these audits were the first PGM mines to be implemented in South Africa, conducted as the world was ramping up from Covid-19 and stakeholder engagements had to be conducted in this context. These audits also had significant delays and challenges associated with Covid-19.

Table 2 provides a summary of the timelines for the different audit stages and the stakeholder engagement involved for each site.

Table 2. IRMA audit details at AAP mines

Site	Stage 1 audit	Stage 2 audit	Verification audit	Interviews		# of employees engaged in audit	# of auditors on-site
				# of employees	# of stakeholders		
Amandelbult	June – July 2021	Virtual:November 2021 (COVID-19 disruptions) May 2022 (5 days on site)	May 2023 (2 days on site)	24 (stage 2) 12 (verification)	45 (excluding gov and municipal rep interviews)	30	7
Mototolo	May – July 2021	Virtual: December 2021(COVID-19 disruption) May 2022 (5 days on site)	22/05/2023 - 23/05/2023 May 2023 (2 days on site)	23 (stage 2) 19 (verification)	22	28	7
Unki (surveillance)	May – August 2022	August 2022 (3 days on site) Chapter 2.6 Feb 2023	n/a	56	26	16	9

Findings

The finding will be presented using the framework suggested in the methodology and look at lessons learnt from

(1) The implementation process
(2) Audit report findings
(3) Release of audit results.

Lessons learnt from the implementation process

From the framework, the lessons from the implementation process will be valuable for other mining companies considering similar audits and can be used when setting up operations for success.

a) Leadership buy-in: This was important as ownership by the site managers and site leadership team resulted in full site team engagement and led to faster delivery of the audit.
b) Opportunity for peer learning: As we engaged in the audit across our sites, we were able to apply cross-site learnings as well as peer learning amongst companies engaged in the IRMA standard.
c) Inter-operability of standards: Our ability to do joint IRMA/ICMM audit demonstrates that we are all striving for the same standard and there is an opportunity to harmonise this.
d) Capability building: There was a need to develop processes for implementing IRMA and building capability in the mine teams on how to complete the self-assessments effectively and prepare for the site visits and associated logistics.

Lessons learnt from the audit report findings

The report findings provided insights into site sustainability performance and these lessons will be beneficial to stakeholders interested in understanding the impact of audits of site performance.

a) Identification of best practice: Contrary to the nature of audits, often deemed as a tick-box exercise, through engaging in this audit we were also able to identify pockets of best practice which we could scale to our other operations. This also allowed us to demonstrate positive impacts that we may have been taking for granted, for instance Zero Waste To Landfill best practices at some sites.

b) Better risk management for the mining sites: Through engaging with audit and subsequent findings, we were able to improve on our on-site practices, inadvertently improving risk management. In the 12-month corrective action period, we were able to improve the condition of our salvage yards, setting a higher bar for the management of non-mineral waste management.

c) Compelling mining companies to go beyond legal compliance allows us to juxtapose international best practice standards with host country regulations (Murguia and Bastida, 2024). It therefore bridges the gap between international and domestic standards by holding companies to the most stringent standards between the two.

Lessons learnt from the release of audit results

With audit results out for three sites, there is a need to understand the impact of sustainability audits on downstream customers and the lessons learned that can be shared are presented below.

a) A higher degree of transparency on operational performance: This is often seen as increasing transparency for external stakeholders but even internally, the transparency across various facets of environmental, social and governance (ESG) has catalysed multi-functional collaboration and alignment, resulting in improved performance.

b) Encourages building better relationships with stakeholders: These audits offer an independent perspective of stakeholder inputs regarding the mine presence and offers us insights that contribute to our operational strategies.

c) Opportunity for regional business development especially if we are all held to the same standard and expectation.

d) Traceability across supply chain: Mining has long, complex and opaque supply chains. Transparency through assurance schemes coupled with technology development can improve traceability in supply chains – allowing for increased and more effective downstream engagement. IRMA reports can serve as a mechanism to facilitate this engagement; we have seen this assisting our efforts.

e) Offers a consolidated view of mine's responsible mining practice beyond typical ESG measures and ratings.

Limitations realised

With all these lessons learnt, we also identified some limitations that came with the process that are worth sharing.

a) Mining standards alone are not sufficient to reach the outcome: Industry-wide performance requires a functioning government, a responsible mining industry and empowered local communities to embed these practices. Good practice by an industry is limited if only one company is doing it, therefore there needs to be increased uptake of standards, particularly in developing nations. Given that these standards are voluntary, a well-functioning regulatory body remains critical. (Miranda *et al*., 2005).

b) Audit results are a snapshot of your performance in time: Summarising performance to a score will always have the unintended consequence of not always being able to effectively capture controversies on the ground. While the full audit report is available to counteract this, these are often too onerous for stakeholders to go through. This also highlights the nuanced nature of audits – reflecting the circumstances at the time of the audit; these often extend beyond the mine borders.

c) Balance between current and future states: Voluntary sustainability standards introduce a higher bar of operation. Certification bodies therefore need to balance this in reporting so as to not discourage further uptake of the standard without watering down what must be done.

d) Historical operations face a significant challenge in retrofitting newer standards that were not in place at the time of initiation: Sites with legacy impacts will often require additional effort to comply with these standards and may find the standards more challenging to undertake. It is also often historic/legacy sites that do not always have baselines, and these are under-researched as they were not required at the time. This affects the extent to which these aspects can be regulated and similarly assured, even by voluntary standards.

e) Consideration of local context: In certain circumstances, these standards may be prescriptive, and these conditions may not be met in certain circumstances. These standards, therefore, although coming as close as possible to a universally accepted definition of best practice, must always be flexible enough to consider certain contexts, or else risk being unimplementable. Similarly, this highlights the need for certification bodies/auditors who understand the local context, highlighting the need to increase capacity-building of local auditors for international standards.

f) Audits that engage with stakeholders assume that all stakeholders engaged act in good faith. There is a need to consider how these views are balanced and triangulated. Additionally, these audits are vulnerable to changes in logistics.

CONCLUSION

Our experience with implementing IRMA has highlighted areas of best practice, where we go beyond legal compliance, and similarly areas where there are opportunities to improve, regardless of the status of legal compliance. Additionally, the participation in an audit process that includes stakeholders has allowed us to embrace a level of vulnerability never experienced before, but similarly has exposed us to some of the blind spots in our current practices, elevating the inputs of some stakeholders that we do not adequately reach in our processes.

As we continue to engage with our audit reports, this has led to an improvement in on-site practices as well as a greater understanding of where there are mismatches between corporate initiatives and the 'on the ground' impact of these, whether intended or not. These standards implore us to go beyond risk management (Gudrun and Schutte, 2022).

It is difficult to draw generic conclusions on the impacts of participating in voluntary sustainability standards, as impacts are case-specific and will be seen over time. This is evidenced with the various AAP sites achieving varying levels of IRMA achievement even though the mine sites are all held to the same internal standards. This variation however does suggest that these audits do work and that they do bring to light nuances in context.

The implementation of voluntary standards has been critiqued as heavily skewed for organisations with well-established organisational structures, marginalising those without (Gudrun and Schutte, 2022). However, we learn from the implementation of sustainability schemes in agriculture that the adoption of standards has enabled access to markets even for smallholders. Therefore while the impacts were not immediate, they were realised over the long-term. Impacts were also seen where certification schemes were adopted, and decreased deforestation rates were seen in some instances (Axel *et al.*, 2022). Without suggesting that the only positive impact for mining companies to participate in voluntary standards is access to markets and the potential of 'green premiums', we do hope to see these as a by-product in the foreseeable future.

There remains an opportunity to leverage and seek alignment and inter-operability of standards as companies contend with standards and determine the most aptly suited standard for their stakeholders.

Naturally, any practice done with the knowledge that it will be in the public domain impels you to put your best foot forward; therefore we cannot underestimate the role of participating in these standards to drive real, lasting impact at a site level. The role of multi-disciplinary standards in driving responsible mining practice therefore cannot be undermined and this is only going to increase with the emergence of due diligence legislation.

Ultimately, we have demonstrated that even the most rigorous standards are feasible to implement, however we do recognise that this is not without effort. Responsible mining extends beyond private assurance and requires sustained commitments and actions to build, sustain and foster trust. We learn from Brumandinho and Mariana (Diego and Bastida, 2024) that governments should never delegate the task of independent oversight, therefore the role of the state remains critical in driving responsible mining practice.

REFERENCES

Miranda, M., Chambers, D. and Coumans, C., (2005). Framework for Responsible Mining: a guide to evolving standards

Goodland, R., (2012) . Responsible mining: the key to profitable resource development. Sustainability, 4(9), 2099 – 2126 2012

Ayeh, D. and Bleicher, A. (2021). One concept fits it all? On the relationship between geoethics and responsible mining. The Extractive Industries and Society 8(3), 100934

Hart, R. and Coumans, C., (2013). Evolving standards and expectations for responsible mining, a civil society perspective

MiningWatch Canada

Di Capua, G ., Bobrowsky, P.T., Kieffer, S.W and Palinkas, C. eds (2021) Geoethics: Status and Future Perspectives. Geological Society of London, Special Publications

Murguia, D.I and Bastida, A.E., (2024). The elephant in the mine: Why voluntary sustainability standards are insufficient to ensure responsible mining. The extractive industries and society (19), 101485

Franken G, Schutte P., (2022). Current trends in addressing environmental and social risks in mining and mineral supply chains by regulatory and voluntary approaches. Mineral Economics, 35(3), 653 - 671

Sauer, P.C., and Hiete, M., (2019). Multi-stakeholder initiatives as social innovation for governance and practice: a review of responsible mining initiatives. Sustainability, 12(1) 236

Marx, A., Depoorter, C. and Vanhaecht, R., (2022)Voluntary. Sustainability Standards: State of the Art and Future Research. Standards, 2(1), 14 -31

Giurco, D. and Cooper, C., (2012) Mining and sustainability: asking the right questions.

Minerals Engineering, 29, 3 – 12,

Moran, C.J., Lodhia, S., Kunz, N.C and Huisingh, D., (2014). Sustainability in mining, minerals and energy: new processes, pathways and human interactions for a cautiously optimistic future. Journal of Cleaner Production (84), 1 - 15

Komives,K. and Jackson,A., (2014). Introduction to Voluntary Sustainability Standard Systems.Voluntary standard systems: A contribution to sustainable development, 3 – 19. Berlin, Heidelburg: Springer Berlin Heidelburg

Ali, S., Mori Junior, R., & Franks, D. M. (2015). Designing sustainability certifications for greater impact - An analysis of the design characteristics of 15 sustainability certification schemes in the mining industry

Bryman, A., & Bell, E. (2011). Business Research Methods (3rd ed.). Oxford

Sekaran, U. and Bougie, R. (2013) Research Methods for Business: A Skill-Building Approach. 6th Edition, Wiley, New York.

Mori Junior, C., Franks, R. M., & Ali, D. M. (2015). Designing Sustainability Certification for Impact: Analysis of the design characteristics of 15 sustainability standards in the mining industry. Centre for Social Responsibility in Mining.

Heinz, R., Sydow, J., & Ulrich, F. (2022). An Examination Of Industry Standards In The Raw Materials Sector How Standards Contribute To Companies' Fulfilment Of Their Human Rights And Environmental Due Diligence Obligations, And How They Ensure Effectiveness On Site Study.

Human Rights Watch. (2022). "Obsessed with audit tools, missing the goal" : why social audits can't fix labor rights abuses in global supply chains.

Bilham, N. T. (2021). Responsible mining and responsible sourcing of minerals: Opportunities and challenges for cooperation across value chains. In Geological Society Special Publication (Vol. 508, Issue 1, pp. 161–186). Geological Society of London. https://doi.org/10.1144/SP508-2020-130

van den Brink, S., Kleijn, R., Tukker, A., & Huisman, J. (2019). Approaches to responsible sourcing in mineral supply chains. Resources, Conservation and Recycling, 145, 389–398. https://doi.org/10.1016/j.resconrec.2019.02.040

INTERNET SOURCES

International Institute for Sustainable Development. Sustainable Development Dhttps://www.iisd.org/mission-and-goals/sustainable-development#:~:text=Sustainable%20development%20is%20development%20that,to%20meet%20their%20own%20needs. Date Accessed: 12 August 2024

United Nations (UN) (1987) Brundtland Report WCED. https://sustainabledevelopment.un.org/content/documents.5987our-common-future.pdf. Date Accessed: 12 August 2024

IRMA (2023) IRMA System Overview. https://responsiblemining.net/wp-content/uploads/2023/12/IRMA-System-Overview-November-2023.pdf Date Accessed: 8 August 2024

IRMA (2022), IRMA Mine Site Assessment Manual, https://responsiblemining.net/wp-content/uploads/2022/09/IRMA-Mine-Site-Assessment-Manual_09-2022-UPDATE.pdf Date Accessed: 12 August 2024

McKinsey, (2024.) State of the Consumer 2024: What's now and what's next. https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/state-of-consumer . Date Accessed: 15 July 2024

Lead the Charge Leaderboard, (2024.) https://leadthecharge.org/scorecards-summary/methodology/ Date Accessed: 20 February 2024

ICMM (2012). The role of mining in national economies, Mining's contribution to sustainable development .https://www.icmm.com/website/publications/pdfs/social-performance/2012/research_romine-1.pdf Date Accessed: 15 August 2024

BBC. (2021). Norilsk Nickel: Mining firm pays record $2bn fine over Arctic oil spill - BBC News. https://www.bbc.co.uk/news/world-europe-56350953 Date Accessed: 15 July 2024

The Guardian. (2020a). Dozens feared dead in Zimbabwe mine collapse as rescue efforts continue | Global development | The Guardian. https://www.theguardian.com/global-development/2020/nov/28/dozens-feared-dead-in-zimbabwe-mine-collapse-as-rescue-efforts-continue Date Accessed: 13 July 2024

The Guardian. (2020b). Rio Tinto blasts 46,000-year-old Aboriginal site to expand iron ore mine | Indigenous Australians | The Guardian. https://www.theguardian.com/australia-news/2020/may/26/rio-tinto-blasts-46000-year-old-aboriginal-site-to-expand-iron-ore-mine Date Accessed: 07 July 2024

The Guardian. (2021). Mining giant Glencore faces human rights complaint over toxic spill in Chad | Mining | The Guardian. https://www.theguardian.com/global-development/2021/jan/28/mining-giant-glencore-faces-human-rights-complaint-over-toxic-spill-in-chad Date Accessed: 28 July 2024

Wall Street Journal. (2020). In Myanmar, Landslide at Jade Mine Kills More Than 160 People - WSJ. https://www-wsj-com.ezp.lib.cam.ac.uk/articles/in-myanmar-landslide-at-jade-mine-kills-more-than-160-people-11593702943 Date Accessed: 15 July 2024

EY. (2021). Top 10 business risks and opportunities for mining and metals in 2022 | EY - Global. https://www.ey.com/en_gl/mining-metals/top-10-business-risks-and-opportunities-for-mining-and-metals-in-2022 Date Accessed: 01 July 2024

Kimberly Process (2023). https://www.kimberleyprocess.com/en/what-kp. Date Accessed: 12 August 2024

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