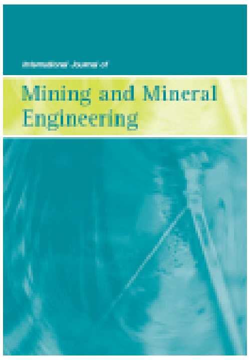
INDERSCIENCE PUBLISHERS
Linking academia, business and industry through research



International Journal of Mining and Mineral Engineering

ISSN online: 1754-8918 - ISSN print: 1754-890X
https://www.inderscience.com/ijmme

A review of the negative impact of adopting fourth industrial revolution technology in South Africa's mining industry

T. Tingini, J. Githiria

DOI: 10.1504/IJMME.2026.10078119

Article History:

Received:	04 September 2025
Last revised:	09 February 2026
Accepted:	14 February 2026
Published online:	12 July 2026

A review of the negative impact of adopting fourth industrial revolution technology in South Africa's mining industry

T. Tingini and J. Githiria*

School of Mining Engineering,
University of the Witwatersrand,
Johannesburg 2050, South Africa
Email: Tinotenda.Tingini@wits.ac.za
Email: Joseph.Githiria@wits.ac.za
*Corresponding author

Abstract: The benefits of fourth industrial revolution (4IR) technologies in mining, such as improved productivity, safety, and operational efficiency, are well documented. However, there remains a limited and fragmented understanding of their negative socio-economic, ethical, regulatory, and security implications, particularly in developing-country contexts such as South Africa. This study addresses this gap by systematically examining empirically observed risks and constraints associated with 4IR adoption in the South African mining sector, distinguishing these from speculative or assumed impacts. The study uses a qualitative narrative review methodology to synthesises evidence from peer-reviewed academic studies, as well as authoritative industry and policy reports. The findings show that 4IR adoption is constrained not only by high capital costs, skills shortages, and regulatory uncertainty, but also by behavioural and cultural resistance. The study concludes that 4IR adoption in mining risks exacerbating inequality and undermining long-term socio-economic sustainability if there are no proactive governance measures.

Keywords: mining; fourth industrial revolution; 4IR; automation; cybersecurity; job displacement; socio-economic impacts; South Africa.

Reference to this paper should be made as follows: Tingini, T. and Githiria, J. (2026) 'A review of the negative impact of adopting fourth industrial revolution technology in South Africa's mining industry', *Int. J. Mining and Mineral Engineering*, Vol. 17, No. 5, pp.1–28.

Biographical notes: T. Tingini is a Lecturer in the School of Mining Engineering at the University of the Witwatersrand and a PhD candidate in Mining Engineering. His research integrates mine transportation systems, mineral economics, and productivity optimisation to strengthen decision-making and sustainability in the mining sector. His work spans mechanised mining performance optimisation, haulage energy efficiency, artisanal and small-scale mining formalisation, and the socio-economic implications of fourth industrial revolution technologies. By combining technical, operational, and economic perspectives, he advances value chain optimisation and sustainable resource governance in mining.

J. Githiria is a Senior Lecturer in the School of Mining Engineering at the University of the Witwatersrand, Johannesburg. He holds a PhD in Mining Engineering from University of Witwatersrand in South Africa, Master of

Engineering Science-Mining from Curtin University in Australia and Bachelor of Science in Mining and Mineral Processing Engineering from Jomo Kenyatta University of Agriculture in Kenya. His research interests include mine planning and optimisation, mine design with the aid of computer technology and operations research application. He has several peer reviewed journals and conference publications. He is a member of the Engineers Board of Kenya (EBK), Australian Institute of Mining and Metallurgy (AusIMM) and the Southern African Institute of Mining and Metallurgy (SAIMM).

1 Introduction

There is a growing global trend advocating for the mining industry to embrace the benefits of digitalisation and other fourth industrial revolution (4IR) technologies. For example, Lund et al. (2024) note a broad consensus among researchers that these innovations have the potential to create more attractive workplaces, which can help address the industry's skills shortage, particularly by appealing to younger generations. Industries such as advanced manufacturing, logistics, automotive, and e-commerce have largely embedded 4IR technologies, including automation, the internet of things (IoT), artificial intelligence (AI), and real-time data analytics, into their core operations already (McKinsey & Company, 2025). However, the comprehensive and integrated implementation of comparable technologies in the mining sector remains relatively slow and fragmented (Alexander, 2022). For instance, in 2016, the World Economic Forum (WEF) predicted that by 2025, the use of automated machinery in the mining industry would be widespread. The WEF (2017a) estimated that by 2025, autonomously run mines would add a value of approximately US$60 billion to the mining industry through productivity improvements and lower labour costs. Contrarily, recent industry research indicates that these early predictions that there would be an extensive adoption of automation in mining operations by 2025 were too optimistic, as they have not materialised as expected so far (Global Data, 2025).

While over 71% of mining firms acknowledge AI, automation, and robotics as possessing the most future impact on their operations, complete automation has yet to be achieved. The present reality is that the mining industry is still working towards addressing the challenges related to setting up the prerequisite infrastructure and dealing with regulatory compliance and human resource development (BDO, 2025). CMIC Global (2025) also notes that while the trend in automation in mines is gradually growing, it remains constrained by capital requirements, regulatory roadblocks, and socio-economic complexities. This includes resistance within the traditional systems and by stakeholders to embrace the change (CMIC Global, 2025).

Grand View Research (2025) projects that the global market for mining automation will grow at a compound annual growth rate of 7% between 2025 and 2030, from a base of US$5.7 billion in 2024. This growth rate forecast is predicted to be fuelled by the rapid technological advancements in AI and robotics and the need to implement this technology to improve mining productivity (Grand View Research, 2025). The key technological innovations driving mining transformation include:

- *Smart sensors* – Enable real-time monitoring of equipment, environmental conditions, and worker exposure to hazards, improving operational efficiency and safety.
- *Drones* – Facilitate rapid site surveys, geological mapping, and inspections in hazardous or hard-to-reach areas, reducing risks to personnel and accelerating decision-making.
- *Autonomous vehicles* – Automate material transport and haulage, minimising human exposure to dangerous conditions while increasing operational productivity.
- *Automated drilling systems* – Enhance precision and efficiency in extraction processes, reducing labour-intensive tasks and limiting worker exposure to high-risk environments.

Collectively, these technologies not only improve productivity and profit margins but also strengthen health and safety outcomes and support the broader digital transformation of the mining sector (Lööw, 2021).

Notwithstanding these widely publicised benefits, there remains a critical gap in systematically understanding the associated risks of Mining 4.0, particularly within developing-country contexts. While international case studies largely emphasise productivity and safety gains, far fewer studies interrogate the unintended socio-economic, ethical, and institutional consequences of 4IR adoption. Reported and emerging risks include workforce displacement, algorithmic bias, heightened cybersecurity vulnerabilities, shortened life-of-mine horizons, and psychosocial stress linked to automation and digital surveillance (Sam-Aggrey, 2020; Corrigan and Laye, 2022; ILO, 2022; WEF, 2025).

Evidence from mining jurisdictions, such as Australia, Canada, and Chile, indicates that rapid automation can exacerbate skills mismatches and regional inequality when governance frameworks, labour protections, and reskilling mechanisms lag behind technological deployment (Australian Government Department of Employment, 2014; WEF, 2020; Candrian and Scherer, 2022). These global experiences point to the absence of an integrated analytical framework that adequately captures the negative socio-economic, ethical, and institutional risks of 4IR in mining, thereby justifying the need for a focused review in the South African context. This review therefore addresses this gap by critically synthesising available literature and cross-sectoral evidence relevant to mining to examine the harms, constraints, and ethical concerns associated with 4IR adoption in South Africa's mining industry.

Within this context, it is important to recognise that the implementation of 4IR technologies introduces complex and often under-examined risks alongside operational benefits (Horberry et al., 2016). For instance, Lacoursiere (2025) introduces the concept of a 'social license to automate', arguing that community acceptance and ethical governance are prerequisites for legitimising automation in mining. Memon and Ooi (2021) similarly caution that while 4IR technologies can enhance efficiency, they may also deepen inequality by disproportionately benefiting capital-intensive firms and high-skilled workers.

In the mining sector, these dynamics are particularly pronounced. Increased automation and digitalisation risk displacing low- and semi-skilled labour, undermining employment opportunities for host communities that are often structurally dependent on mining for livelihoods (Cosbey et al., 2016). At the same time, the shift toward digitally integrated and automation-intensive supply chains may marginalise local suppliers who lack the financial resources, technological capabilities, or skills required to meet new procurement standards (Lund et al., 2024). These challenges are further compounded in developing economies, where institutional capacity, regulatory enforcement, and workforce reskilling systems frequently lag behind the pace of technological change (ILO, 2022).

The South African mining sector presents a critical case against this backdrop. While it is actively pursuing Mining 4.0 to remain globally competitive, it operates within a socio-economic environment characterised by high unemployment, deep inequality, and historically contested labour relations. As such, the adoption of 4IR technologies in this context raises important questions regarding employment sustainability, ethical governance, social cohesion, and long-term community resilience. Addressing these concerns requires moving beyond a predominantly techno-optimistic narrative toward a balanced assessment that explicitly interrogates risks, trade-offs, and unintended consequences.

Accordingly, this study seeks to contribute to literature by providing a structured synthesis of the negative impacts, constraints, and ethical risks associated with 4IR adoption in the South African mining industry. This review aims to inform policymakers, regulators, industry stakeholders, and labour representatives on the conditions under which Mining 4.0 can be pursued responsibly and inclusively. It will do so by consolidating fragmented evidence from mining-specific studies and relevant cross-sectoral research.

Empirical evidence as discussed in this paper indicates that digitalisation introduces new ethical challenges and cybersecurity vulnerabilities. These extend into critical infrastructure, posing national security risks and creating labour market disruptions, including direct, indirect, and transitional job losses. Additionally, efficiency gains associated with automation can accelerate resource depletion and shorten mine life, amplifying the socio-economic risks for mining-dependent communities.

2 Methodology

This paper adopted a qualitative narrative review methodology to examine the negative impacts, limitations, and risks associated with the adoption of 4IR technologies in the mining sector, with a specific focus on South Africa. A narrative review was selected due to the interdisciplinary and emergent nature of the Mining 4.0 risks, where empirical mining-specific case studies remain limited and evidence is dispersed across academic, policy, and industry sources.

A purposive sampling strategy was employed to identify relevant literature. Sources were drawn from peer-reviewed journals, policy documents, and industry reports accessed through academic databases, including Scopus, Web of Science, and Google Scholar. Additional grey literature was sourced from reputable institutions, such as international organisations, government departments, and mining regulatory bodies. Inclusion criteria focused on publications that explicitly addressed automation, digitalisation, AI, cybersecurity, labour impacts, ethical governance, or socio-economic outcomes in mining or closely related industrial sectors. Non-credible sources and publications lacking methodological transparency were excluded.

The data collection process involved a two-stage screening approach. First, titles and abstracts were reviewed to assess their relevance to Mining 4.0 risks. Second, full-text screening was conducted to ensure conceptual alignment with the study's focus on negative impacts and governance challenges. This process enabled the refinement of the literature corpus while maintaining analytical relevance and depth. Data was analysed using a qualitative thematic analysis framework. Key themes were identified through iterative coding. The researcher focused on recurring patterns related to ethical risks, workforce impacts, cybersecurity vulnerabilities, governance gaps, operational safety concerns, and socio-economic consequences. Cross-sectoral evidence was analysed comparatively to identify structural parallels and transferable risk dynamics relevant to mining, while avoiding direct causal generalisations where empirical mining evidence was limited. The review triangulated the findings across multiple source types and jurisdictions to enhance its reliability and analytical rigour. Conceptual consistency was prioritised by cross-referencing claims against multiple independent sources. All limitations related to data availability and contextual transferability are explicitly acknowledged, and the findings are presented as evidence-informed insights rather than definitive causal conclusions.

3 Classification of barriers to the adoption of 4IR or IoT

Although the adoption of 4IR and IoT technologies in mining faces several barriers, these challenges are often offset by potential benefits, such as improved operational efficiency, enhanced worker safety, and predictive maintenance capabilities. Global Data (2024) conducted a survey called 'The Global Mine-Site Technology Adoption Survey' to examine these barriers in context. The examination was based on structured interviews with key decision-makers and technical personnel (such as mine managers and mine-site IT or operations managers) at 162 operating mine sites globally. Only one response was accepted per mine. The sample covered a geographically diverse set of mining regions, with 33% of the respondents from Africa, 28% from the Americas, 17% from Asia, 14% from Oceania, and 8% from Europe and the Middle East. In terms of mine characteristics, approximately 50% of the responses were from surface-only operations, while 33% were from underground only operations, and 17% were from mixed surface-underground operations. The survey also reflected a balanced industry structure, with 54% of the responses drawn from major mining companies, and 46% drawn from mid-tier or junior producers.

The survey analysed the barriers limiting the uptake of 4IR technologies in the mining sector, including drones, autonomous vehicles, and mine management software. The results, illustrated in Table 1, indicate that the most significant barrier to 4IR adoption (54%) is the perception that these technologies are not yet sufficiently proven (Global Data, 2024). This perception reflects the mining industry's requirement for demonstrable operational evidence before committing to large-scale adoption. Firms typically seek both extensive pilot implementations and longer operational track records that demonstrate consistent performance, measurable return on investment (ROI), and tangible improvements in safety, productivity, or cost efficiency (Pakdel and Erol, 2025). Validated pilots in comparable operational settings also allow companies to assess integration challenges, workforce readiness, and system interoperability, thereby providing confidence for broader deployment (PwC et al., 2023). Consistent with this, the research by Sithole (2024) showed that organisations often delay adoption when technologies are perceived as complex or immature. This underscores the importance of documented case studies, operational success, and quantifiable business benefits as proof points for decision-makers. This view is further supported by Florida et al. (2018), who identified technological maturity and trust in 4IR-operated systems as major barriers in high-risk industries, such as mining. Ghosh (2020) also noted that the sector's inherent investment risks, arising from commodity price volatility and long payback periods, drive a preference for more proven operational methods.

Table 1 Main barriers to 4IR adoption in the mining industry

Barrier	*% of respondents*
Technology needs to be more proven	54
Cost of technology	48
Skills required	35
Regulatory uncertainty	33
Not a focus for company leadership	12
Limited return on investment	9

Source: Global Data (2024)

The cost of 4IR technology (48%) was also revealed to be the other significant concern. 4IR technology often needs major upfront capital investment to enable the integration of the prerequisite infrastructure systems, which can often act as a deterrent to the adoption of 4IR technology (Florida et al., 2018). Nyagadza et al. (2021) also identified high capital costs (CAPEX) as a major challenge for firms when they attempt to adopt 4IR technology. The high capital costs of implementing 4IR technology are even more prohibitive in mines. This is because the infrastructure upgrades required to facilitate the integration of technologies like automation, AI, and IoT with the pre-existing mining layouts and legacy systems are both a complex and a costly endeavour (Datta, 2022).

A skills shortage (35%) was also identified as a major barrier to the adoption of 4IR technology. Sam-Aggrey (2020) argued that there is limited knowledge and expertise to implement and manage new technologies due to the novelty of some of the new technology associated with the 4IR. Hewapathirana and Almasri (2021) explained that the 4IR demands new skills, such as data analytics, AI literacy, and digital systems integration. Shortages in these competencies hinder technology adoption by increasing implementation risks, delaying deployment, and limiting organisations' ability to operate effectively and extract value from the advanced digital technologies. Tsiligiris and Bowyer (2021) also identified the current mismatch that exists between the type of skills currently being taught in higher education institutions and the skills required for 4IR readiness, further amplifying the skills gap. Gonese and Ngepah (2024) showed that without targeted investment in 4IR-related training and education, these technologies risk becoming a significant threat to employment and may further exacerbate inequality. This finding aligns with global evidence indicating that gaps in digital, analytical, and technical skills constrain 4IR adoption and contribute to unequal labour-market outcomes, particularly in regions such as Africa and South Asia (WEF, 2020). These challenges are especially pronounced in sectors like mining, which have historically relied on unskilled and semi-skilled labour roles that are increasingly vulnerable to displacement by automation and other 4IR technologies.

Regulatory uncertainty was identified as a significant barrier to the adoption of 4IR technologies in the mining sector (33%) (Global Data, 2024). Jones et al. (2025) explain that this uncertainty largely arises from the fact that the EU Artificial Intelligence Act (Regulation (EU) 2024/1689) is the first and only comprehensive, standalone AI specific legislation currently in force, while most other jurisdictions have yet to implement comparable AI focused regulatory frameworks. This, when combined with the inherent lag between rapid 4IR technological advances and the slower pace of lawmaking, creates uncertainty around compliance, liability, and implementation. The Act classifies AI systems by risk and imposes strict obligations on high-risk applications, including conformity assessments, transparency, and human oversight. While these measures aim to protect users and society, they can also slow innovation and adoption. Kjaer and Vetterlein (2018) noted that regulatory frameworks often struggle to keep pace with rapidly evolving sectors, and the IMF (2024) observed that legislative processes frequently lag behind technological change. Olaleye et al. (2022) further amplified how uncertainty regarding the legality of emerging 4IR technologies, including data protection issues and liability concerns, hinders innovation and the willingness to adopt these emerging technologies.

Studies have also shown that there is a lack of prioritisation of 4IR technology adoption by mine management. Survey data shows that 12% of mines reported insufficient focus from management and workforce resistance, which is frequently tied to job loss concerns (Global Data, 2024). Ghosh (2020) similarly highlights social resistance and cautious attitudes toward AI deployments in mining as contributing factors to the slow pace of implementation. Limited ROI is another key barrier, with 9% of the mines surveyed by Global Data (2024) identifying this as a concern. According to Manyuchi et al. (2020), both uncertainty and limited ROI are a major factor for mining companies when considering the adoption of 4IR technology. The combination of substantial initial implementation costs and unclear short- to medium-term financial returns frequently deters investment in emerging technologies like IoT and AI in the mining sector.

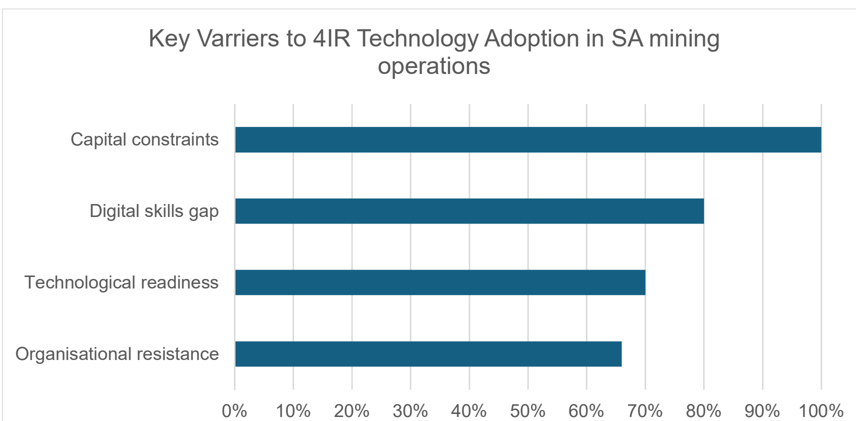
Furthermore, Ediriweera and Wiewiora (2021) noted that reliance on outsourcing for a significant proportion of 4IR technologies and associated software introduces supplier dependency, complicating ROI assessment and increasing operational risks. These include dependency on external vendors for system integration and maintenance, potential delays or disruptions in operations, limited control over software customisation, and challenges in ensuring data security and compliance. Moreover, reliance on outsourcing technological services to third-party providers complicates the accurate assessment of ROI and can reduce organisational flexibility in adopting or scaling technologies (Manyuchi et al., 2020). Collectively, these studies demonstrate that both managerial prioritisation and financial considerations are critical factors shaping the adoption of 4IR technologies in mining operations.

The global evidence in this section highlights the common impediments to 4IR and IoT adoption, such as technology maturity, cost, skills, regulatory uncertainty, managerial prioritisation, and ROI. However, it is important to note that the extent and manifestation of these barriers are also context dependent (Global Data, 2024). South African mines operate within a distinct regulatory, infrastructural, and socio economic environment that includes legacy systems, skills pipeline constraints, and compliance requirements specific to national frameworks. These factors can amplify or modify the global barriers described above. Section 4 narrows the lens to the South African setting. The section examines how these factors play out in practice and identifies the primary barriers to 4IR investment reported by South African operations.

4 Main barriers to 4IR investment in South African Mines

Building on the global barriers outlined in Section 3, this section focuses on how these challenges intersect with South Africa's mining context and introduces additional constraints unique to the region. Survey findings by Lumadi and Nyasha (2024) indicate that South African mines face four dominant impediments to 4IR adoption: limited capital funding, shortages of digital skills, low technological readiness, and behavioural resistance. Figure 1 summarises these results, which underscore the need for a closer examination of each factor to understand their implications for 4IR investment in South African operations (Lumadi and Nyasha, 2024). Exploring these barriers in detail provides the evidence base necessary to inform targeted strategies and policy interventions that can support successful technology adoption.

Figure 1 Top four barriers to 4IR technology adoption on South African mines (see online version for colours)



Source: Lumadi and Nyasha (2024)

In the South African mining industry, investment in research and development (R&D) for the deployment of novel mining technologies remains constrained (Alexander, 2022). The WEF (2023) highlighted how African countries, including South Africa (SA), only spend less than 0.5% of their gross domestic products (GDPs) on R&D on average. This spend is significantly lower than the 1.7% global average. This relatively low level of R&D investment constrains the development of local innovation ecosystems, pilot initiatives, and skills pipelines, thereby indirectly limiting the readiness of South African mining operations to adopt and scale 4IR technologies. Stander and Broadhurst (2021) argued that the high costs and extended development timelines associated with advanced mining technologies discourage sustained R&D investment. Lumadi and Nyasha (2024) further noted that uncertainty regarding financial returns exacerbates this challenge, leading to underfunding and limiting the adoption of 4IR technologies.

These investment constraints are reflected in formalised innovation outputs, as evidenced by Steenkamp et al. (2025), who reported a decline in South Africa's share of global mining patent registrations from 10% in 1995 to approximately 4% in 2024. The researcher acknowledges that a substantial portion of mining-related innovation, particularly process optimisation and site-specific technological adaptation, is not patented. Regardless, this decline in patent registrations is used in the study as a partial indicator of reduced engagement in capital-intensive, long-horizon R&D activities that are critical for the development and scaling of advanced 4IR technologies.

The study conducted by Obagbuwa and Munzhelele (2024) also found underinvestment by mining firms in South African mines as a challenge to implementing 4IR technology adoption. In other words, fewer and fewer mining companies are investing in SA's mining industry, particularly in greenfield projects, where the adoption of 4IR technology is easier to implement. Most of the mining companies that have remained invested in SA's mines have reduced their capital expenditure (CAPEX) and are now mainly focused on providing capital to sustain their existing operations (Indurjeeth, 2021). This is particularly the case in the platinum industry. The current climate makes it challenging to introduce new advanced technologies in South African mines.

The study by Obagbuwa and Munzhelele (2022) identified persistent underinvestment by mining firms in SA as a key constraint to the adoption of 4IR technologies, particularly in greenfield projects where digital systems can be integrated more effectively from the outset. This pattern is evident in the platinum mining sector, where major producers have increasingly reduced growth-oriented CAPEX and prioritised sustaining existing operations amid rising costs, regulatory uncertainty, and subdued investor confidence (PwC, 2023). For example, corporate disclosures from the leading platinum producers, namely Anglo-American Platinum and Sibanye-Stillwater, indicated a strategic shift toward maintenance and sustaining CAPEX, with limited allocation toward new projects or large-scale technology deployment (Anglo American Platinum, 2023; Sibanye-Stillwater, 2023). This investment climate constrains the introduction of advanced 4IR technologies, which typically require significant upfront capital, long implementation timelines, and stable investment conditions to support successful adoption (Indurjeeth, 2021).

The low availability of appropriately skilled workers also inhibits the adoption of 4IR technology in South African mines. This is exacerbated by the fact that a significant proportion of South Africa's population lacks an adequate level of formal education. This results in mining firms struggling to find personnel with the required digital skills to implement 4IR technology (Alexander, 2022). A report by the ILO (2023) highlighted the consistent skills gap in South Africa. It noted that there is a mismatch between educational training outputs and the industry's skills demand, resulting in most of the country's workforce lacking the required knowledge and skills for emerging cutting-edge technologies. The SA Department of Higher Education and Training (2024) conducted a study which revealed structural imbalances within the country's labour market. The department found that on one hand, there is a persistent oversupply of low-skilled labour. On the other hand, there is a huge scarcity of highly skilled professionals, particularly in the technical fields needed for 4IR.

The Mandela Mining Precinct (2022) study examined the South African mining sector's preparedness for technology adoption using qualitative case studies at two modernising mines. Data collection comprised focus group discussions with adult education learners, mineworkers enrolled in training programmes, contractors, and community youth (a total of 35 participants across both case studies). Data collection also included key informant interviews with training managers, facilitators, HR supervisors, and skills development personnel, as well as desktop reviews of existing digital training programmes and platforms. The findings revealed widespread gaps in foundational numeracy and digital skills, inferred from the participants' engagement, observations, and programme assessments. The gaps indicated that insufficient workforce skills remain a major constraint to 4IR adoption in mining unless accompanied by sustained investment in education and targeted upskilling (Mandela Mining Precinct, 2022).

Smit and Mji (2012) conducted a quantitative assessment of numeracy skills among unskilled and semi-skilled workers in three South African chrome mines to measure empirically the foundational mathematical competence relevant for workplace learning and technology readiness. The study's target population was 1,053 workers, of whom 873 voluntarily participated in the assessment. The researchers used a standardised academic achievement test designed to assess basic numeracy competence, accompanied by a questionnaire to collect biographical information. The results showed that only 12 workers (1.4%) were numerate, meaning that 98.6% lacked basic numeracy skills (Smit and Mji, 2012). This indicates an almost universal lack of functional numeracy among entry-level mineworkers, which poses a major barrier to technology adoption and workplace safety.

Low technology readiness in the adoption and operationalisation of 4IR technologies within mining operations was identified as a key inhibiting factor in South Africa's mining sector. A PwC (2023) conducted a survey of South African mining companies and found that immature data management systems (53% of the respondents) and insufficient digital and technical skills (47%) were the most significant barriers to 4IR adoption. Immature data systems limit mines' ability to collect, integrate, and analyse operational data, which is a prerequisite for deploying 4IR applications such as automation, predictive maintenance, and data-driven decision-making. Concurrently, skills shortages constrain the workforce's capacity to implement, operate, and maintain these technologies. Together, these factors reduce organisational readiness for digital transformation, thereby directly slowing the pace and scale of 4IR implementation in South African mining operations. Belur (2024) also highlighted the low maturity level of 4IR technology in SA mining companies, with low technology readiness being identified as a barrier to new technology adoption.

Behavioural change resistance was also identified as a barrier to SA's adoption of 4IR technologies. Lumadi and Nyasha (2024) emphasised that efforts to implement new systems or technologies are unlikely to succeed without corresponding changes in individual behaviour. Shrivastava (2025) argued that this resistance is driven by a lack of trust in 4IR technologies. Ethical considerations, privacy concerns, and security issues, as well as a lack of understanding of the technologies, lead to a lack of confidence amongst the users. Khoza (2025) postulated that this behavioural change resistance is a result of fear by workers and unions that automation will result in job losses, particularly in the mining sector, where many workers have lower skill sets. Beyond individual apprehension, broader community and labour market dynamics also shape resistance to technological change.

For instance, Mnwana and Bowman (2018) found that increased mechanisation in South African mining, while promoted as necessary for economic viability, reduces demand for unskilled labour and limits local economic benefits. This reduced demand exacerbates distributional conflict between mining operations and surrounding communities (Mnwana and Bowman, 2018). This contributes to social tensions and reinforces perceptions that technological change can deepen inequality and marginalise workers and rural residents. Such findings underline that resistance to mechanisation and automation reflects not only individual or union concerns but also wider socio economic anxieties about employment security, equitable distribution of mining benefits, and community well-being in labour intensive sectors.

Smith and Sepasgozar (2022) also identified cultural resistance as an additional barrier to the adoption of new technologies. Cultural resistance is defined as the ways in which prevailing social norms, institutional practices, and collective attitudes can limit the adoption of new technologies or supportive policies. Smith and Sepasgozar (2022) illustrated this as a barrier in their UK-based study in which the low uptake of government-introduced R&D tax incentives reflected an entrenched culture of resistance within parts of the construction and mining ecosystem. This was further evidenced by firms' reluctance to engage with policy instruments designed to stimulate 4IR innovation, demonstrating how weak institutional responsiveness can inhibit technological transformation despite the availability of supportive regulatory mechanisms. Molobi (2024) used a qualitative approach, guided by the technology-organisation-environment (TOE) framework, to analyse semi-structured interviews with senior ICT leaders and stakeholders in an SA government department. Molobi's (2024) study linked leadership resistance and organisational culture to the slow pace of technology adoption using thematic coding. He showed that employee attitudes toward new technologies, limited digital skills, and internal resource constraints are shaped by organisational norms and leadership practices, which in turn undercut 4IR implementation momentum. Together these studies highlight how culture, leadership barriers, and technology readiness all play a role in influencing 4IR technology adoption.

It is therefore important to unpack the potential negative impact of 4IR technology in the mining sector to establish if these fears are indeed founded. The next section aims to conduct a holistic evaluation of the negative impact of adopting the 4IR technology in the mining industry.

5 Negative impact of 4IR adoption in mining

This section aims to conduct a holistic evaluation of the negative impact of adopting the 4IR technology in the mining industry.

5.1 Ethical considerations

Drones are now used extensively on mining sites for various applications, including mapping, surveying, inspections, and smart surveillance. This includes the use of unmanned and autonomous aerial vehicles in conducting aerial photogrammetry and aerial scanning, etc., to collect, process, and analyse the data of interest using remote sensors and integrated software (Vangu, 2022). However, the capability of such technology to gather large quantities of data raises concerns about privacy. For instance, if surveillance technology is adopted to monitor the mining environment, there is a high risk that this technology can be abused. It can resultantly then be used for the monitoring of employees and surrounding community activities in ways that can defy community expectations and ethical principles (Corrigan and Laye, 2022).

In its White Paper about the data economy, the WEF (2021) highlighted the need for ethical data governance and warned against data misuse and unchecked surveillance. Under SA's 'Protection of Personal Information Act (POPIA)', the collection of personal data requires informed consent, whether collected via automated or manual means. The personal data must also be processed in accordance with the law (SA Government, 2014). The SA Government had to promulgate this law partly due to the growing privacy problems that are arising due to the widespread adoption of technological advancements. This is because of the low cost, easy accessibility, and widespread use of smart surveillance. The use of surveillance technology like drones without sufficient transparency can result in unsanctioned monitoring of people, misuse of data, and worker distrust. There is a growing fear by society that people are constantly being watched (Power et al., 2021). Mining companies have also been criticised for harnessing drones and other surveillance technology to monitor workers' private lives (Opray, 2016).

Another ethical concern with the adoption of 4IR technology on mining sites is the moral responsibility that comes with assigning decision-making to machines like autonomous navigation and safety AI-powered systems (Candrian and Scherer, 2022). Delegating life-impacting decisions to non-human systems risks reducing human accountability. This raises ethical concerns about the appropriate role of humans in critical safety decisions. Proponents of AI often argue for minimal human interference, suggesting that reducing human involvement can prevent incidents caused by human error (Mallreddy and Vasa, 2022). However, evidence indicates that human error is rarely the sole cause of mining accidents. For example, a systemic analysis of 91 accidents in a South African platinum mine identified routine violations as frequent but concluded that systemic factors (e.g., inadequate leadership and physical environment problems) were the chief causes of accidents (Bonsu et al., 2017). Broader accident analyses indicate multi-cause chains in which human performance interacts with context (shift scheduling, experience, equipment, and environment), and that errors rarely act as the sole cause (Patterson, 2009; MHSC, 2021). Consequently, human oversight should be maintained, not as a transfer of responsibility, but as an integral safety function within autonomous operations (Ruiz-del-Solar, 2025). In particular, decisions involving life-changing risks should remain under human supervision (Trotta et al., 2023; Global Mining Guidelines Group, 2024).

Caruana (2024) used case studies to illustrate the risks associated with the adoption of autonomous vehicles, drawing particular attention to safety system malfunctions. These incidents underscore critical implications during the transitional phase when 4IR technologies are being introduced into mining operations. The transitional phase is the period when such operational risks are most likely to emerge (Caruana, 2024). Conversely, the proponents of self-driving vehicles and autonomous machines argue that getting rid of drivers and machine operators will make work safer. They cite statistics that state that more than 90% of accidents are due to human error. Critics of automation, however, contend that accidents are more often rooted in systemic failures, such as inadequate system design, poor environmental conditions, or insufficient sensing and control architectures. Human error typically represents the final link in the accident causation chain. From this perspective, automation does not eliminate risk; it shifts it from 'human errors in operations' to 'human errors in coding' (Institute of Electrical and Electronics Engineers, 2023).

In high-risk environments such as mining operations, failures of autonomous systems can have immediate and severe physical consequences. Moreover, AI failure modes are difficult to anticipate, and the probabilistic estimation algorithms underpinning autonomous systems often struggle to make reliable judgements under conditions of uncertainty (Costello and Watts, 2014). Given the inherent variability, environmental complexity, and unpredictability of mining operations, AI-powered autonomous machines face a heightened risk of making erroneous or sub-optimal decisions.

A growing body of research also highlights algorithmic bias and worker well-being concerns associated with AI used in predictive maintenance, workforce management, and performance monitoring. Algorithms are trained on historical data that may encode racial, gender, or other socio demographic biases (Bandara et al., 2025). If left unchecked, these biases can perpetuate and amplify unfair treatment in decision making systems, such as scheduling, task assignments, performance scoring, or workforce evaluations. This then reinforces structural inequalities within organisations, disadvantaging already marginalised workers (ILO, 2022).

Beyond fairness, algorithmic management systems often operate as continuous surveillance tools that reduce worker autonomy and create perceived threats, which can have significant psychosocial costs. Research indicates that algorithmic oversight and constant monitoring are associated with heightened stress, anxiety, emotional fatigue, and a reduced sense of control. All of these contribute to job burnout and diminished well-being (Zayid et al., 2024). The intrusive nature of real-time performance tracking or automated decision systems can undermine essential psychological needs, such as autonomy and relatedness, precipitating negative mental health outcomes such as anxiety, depressive symptoms, and poor sleep quality (OECD, 2025). Additionally, the shift toward remote, algorithm managed roles can lead to social isolation, reducing informal coworker interactions and weakening social support networks that are critical for resilience and workplace satisfaction (García-Ruiz and Rocchi, 2025). These psychosocial effects highlight that while AI and automation can improve efficiency, their unintended consequences on fairness, worker dignity, and mental health must be carefully governed. They can be governed through transparency, human oversight, and ethical labour practices to protect worker well-being in mining and similar labour intensive sectors.

5.2 Cybersecurity vulnerabilities

The adoption of 4IR technologies increases system interconnectivity through automation, IoT, and digital platforms, thereby expanding the attack surface for cyber threats and increasing exposure to data breaches and cyberattacks (McKinsey & Company, 2014). Mining operations are classified as critical infrastructure due to their role in national economies, energy security, and export revenues. Beyond financial and data-related risks, these operations are increasingly vulnerable to state-sponsored or terrorist cyberattacks. Cyberattacks are defined as politically or strategically motivated cyber operations aimed at disrupting, sabotaging, or coercing essential services and industrial systems to achieve geopolitical or ideological objectives (CISA, 2025). Such attacks elevate cyber risk from an operational concern to a national security threat, particularly where disruptions to mining can cascade into energy supply chains, employment stability, and fiscal revenues.

This heightened risk contributes to organisational caution toward full digital transformation. Empirical evidence supports these concerns. A survey conducted by the CSIR (2024) involving over 300 South African firms found that approximately 88% experienced at least one ICT security breach within a one-year period. Most of the affected firms reported repeated attacks, as highlighted in Table 2. The most common attack vectors included malware, application-level attacks, and insider threats (CSIR, 2024). These findings underscore that cyber risks in digitally enabled environments are persistent and systemic rather than isolated events. While the survey does not explicitly disaggregate respondents by sector or specifically identify mining companies, it indicates that participating firms were drawn from a diverse range of industries. Given the mining sector's increasing reliance on interconnected ICT systems, industrial control systems, and digitally enabled operational technologies, the prevalence of cybersecurity breaches reported in the survey has direct relevance for mining operations.

Table 2 Number of incidents SA firms experienced in the past year

Number of breaches	*Percentage of firms (%)*
2–5 breaches	48%
6–9 breaches	23%
None	12%
1 breach	9%
10+ breaches	8%

Source: CSIR (2024)

Given this threat landscape, the mining industry must transition from reactive cybersecurity approaches, which respond to incidents after they occur, to proactive and preventive strategies. Such strategies emphasise threat intelligence, continuous monitoring, secure-by-design systems, employee cyber-awareness, and resilience planning for critical infrastructure protection (Computer Security Resource Centre, 2023). Without such a shift, the growing digitalisation associated with 4IR adoption may amplify vulnerabilities rather than enhance operational resilience. Table 3 shows the results of the study that the WEF (2025) conducted to evaluate the impact of cyber incidents. The top 3 most cited impacts of cyber-attacks where financial loss, brand sabotage, and human safety and health. Even one cyber-attack incident has the potential to result in a very negative high impact.

Figure 2 provides a flowchart illustrating the potential impact of an IoT breach. Vulnerabilities in the IoT systems could provide entry points for hackers to gain unauthorised access to a firm's ecosystem. This could result in hackers being able to steal sensitive information and disrupt critical services and processes in the firm's operations. This could then lead to major negative impacts, including financial and reputational loss, and negative safety and environmental effects (CISA, 2024).

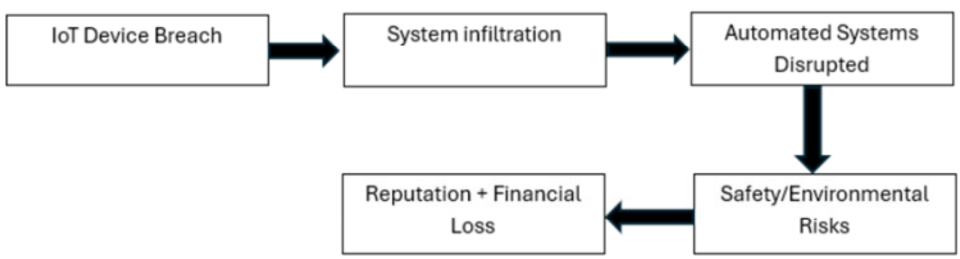
Mining operations are increasingly becoming potential targets for cyberattacks with the growing digitalisation of mines. Brancati et al. (2025) highlighted that the increased digital dependence that comes with the rolling out of automation network systems infrastructure increases the vulnerability of mining operations to external cybersecurity threats. In the mining environment these malicious attacks could result in catastrophic repercussions, including operational disruptions and compromised mine safety.

Table 3 Most cited consequences of cyber incidents

Consequence	*Percentage*
Financial loss	28%
Brand sabotage	19%
Human safety and health	17%
Intellectual property theft	13%
Supply chain disruption	9%
Product delivery	7%
Environmental damage	5%

Source: WEF (2025)

Figure 2 Flowchart outlining the potential consequences of an IoT systems breach



Source: CISA (2024)

For instance, hackers could intercept the wireless communication from drones conducting 3D mapping of a mine (Girma and Brown, 2024). Barbudhe (2024) classified this interception that could result from attacks on drone transmissions as jeopardising privacy. On mines, hacked mapping data could give away sensitive geospatial information, operational data, and access routes. Malicious actors could exploit all this information to target the operation or for sabotaging purposes. Sun et al. (2019) highlighted that drones' communication systems are particularly vulnerable to jamming and eavesdropping due to their wireless infrastructure design. On a mining operation, hackers could extract and manipulate sensitive mine data mid-transmission or install malicious malware undetected.

A digitalised mine utilises numerous networks of sensors as part of its autonomous machine systems, which generate tons of data that is transmitted over the IoT. These IoT sensors include pressure sensors, obstacle sensors, and accelerometers which can be hijacked and manipulated to read false data (Li et al., 2023). On a mine operation, this can result in disastrous scenarios. For example, if a gas sensor is manipulated to underreport the levels of methane in an underground mine, this can lead to a methane build-up, resulting in a fatal gas explosion. If ventilation systems are hijacked and shut off, this can result in a cut-off oxygen supply or a build-up of noxious gases underground.

There have been various case studies highlighting the increasing risks that mining companies face due to cybersecurity. For instance, the Copper Mountain Mining Company (2022) released a press statement stating that it had experienced a ransomware attack at its corporate offices. As a precautionary measure, the company shut down its processing mills for eight days. In addition, it switched its operations from automated back to manual processes where possible. Although no environmental or safety incident was reported, the cyberattack led to significant operational disruptions and financial losses (Copper Mountain Mining Company, 2022).

In 2023, Rio Tinto also experienced a ransomware cyberattack. Hackers exploited the vulnerabilities of contracted data management software to gain access to and leak Rio Tinto's employee data, including payroll information and their personal information. This data was reportedly then uploaded onto the dark web (Tilo, 2023). In 2023, Sibanye-Stillwater also fell victim to cybercriminals. They targeted its ICT system, resulting in the disruption of its global operations (JSE, 2024). Cybersecurity is now rated in the top five operational risks by most mining companies, as the natural resources sector is becoming one of the most targeted (Tunnicliffe, 2024). The cybersecurity risk is only going to increase with the adoption of 4IR technology like IoT, drones, and automation.

5.3 Relationship between job displacement, socio-economic and 4IR

The adoption of 4IR technology in South Africa threatens to disrupt the country's job market in multiple ways. For instance, the global green economy drive, coupled with automation, remote operations, and AI, has already begun to reshape the labour demand across mining and energy value chains (Karolia-Hussain and Fourie, 2021). Figure 3 illustrates this transition, depicting the shift from coal to renewable energy. On the left is a coal mining operation supplying a power plant that is about to be decommissioned, resulting in workers leaving these sites. On the right is a modern solar and wind facility operated remotely via a control centre and employing fewer specialised personnel (IRENA, 2023). This is a visual proxy for how 4IR can reduce on site headcounts, even when new capacity is added.

Job losses can be categorised into three types to understand these impacts better:

- Direct losses, such as truck drivers and machine operators displaced by autonomous haulage systems and automated drilling technologies (Attarbo, 2025).
- Indirect losses, which occur when a reduced on-site workforce leads to contraction of local support services, such as catering, transport, and maintenance, affecting community-level employment (IRENA, 2023).
- Transitional losses, where jobs disappear in one domain (e.g., coal mining) while new roles emerge in others (e.g., renewable energy or digital operations). However, severe skills gaps prevent displaced workers from accessing these opportunities (IEA, 2024).

This categorisation highlights that the socio-economic impact of 4IR extends beyond immediate redundancies to include ripple effects on local economies and structural skills challenges. In coal-dependent municipalities, scholars and policy briefs stress the need for place-based reskilling, social protection, and repurposing of mining assets (e.g., land and water rehabilitation for new value chains) to prevent deepening inequality during decarbonisation (Tamasiga, 2025) Overall, addressing these risks requires proactive transition planning, combining skills development, mobility support, and social dialogue, to ensure that the productivity and safety gains of 4IR do not come at the expense of equity and community resilience (Wills, 2025).

Figure 3 A visualisation of the coal-to-renewables energy transition structural and technological shift (see online version for colours)

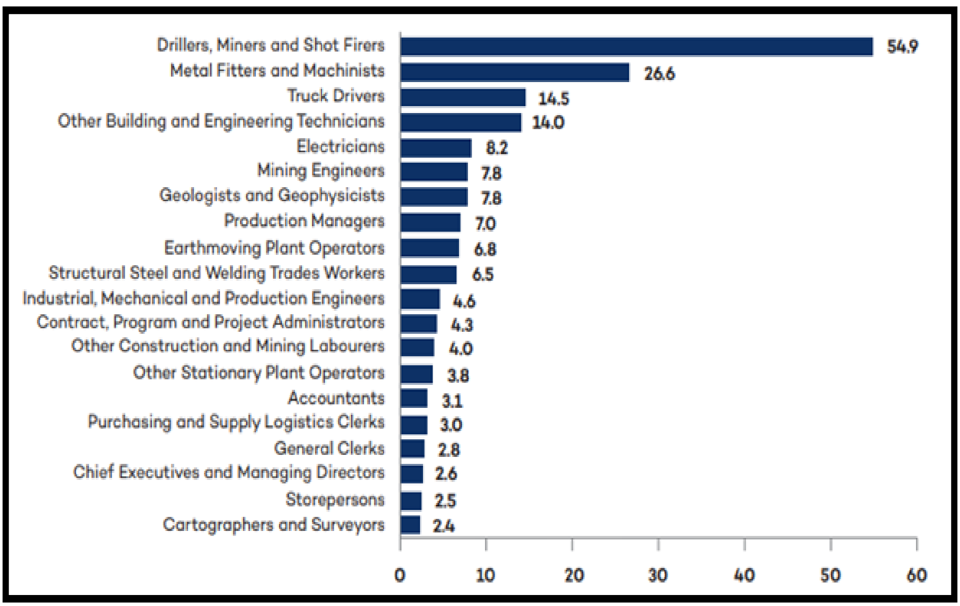
Source: Microsoft Copilot (2025)

The SA Parliament's Portfolio Committee on Energy raised concerns about socio economic impacts during its oversight visit to the Komati coal power station (SA Parliament, 2025). This power station was decommissioned as part of a World Bank supported initiative to decommission and repurpose the site for cleaner energy generation (World Bank, 2022). The committee and other stakeholders highlighted that although some workers were redeployed or reskilled, the retirement of the coal plant has substantially reduced employment opportunities compared with its operation. Former employees and local contractors have experienced loss of livelihoods and there has been weaker economic activity in the surrounding community since the closure of the plant (Erasmus, 2024). This reflects the broader challenges in transitioning a coal dependent community toward a green economy. Alternative opportunities in renewable energy and advanced technological systems have been slow to materialise as traditional coal related employment contracts diminish. This has left workers and local suppliers economically exposed. Moreover, the shift to renewables, tied to low carbon development pathways and enabled by digital and automated systems, often requires more specialised technical skills and fewer on site workers. This underscores the structural labour market changes associated with 4IR technologies (Labuschagne, 2025).

It is estimated that over 70 million jobs are going to be displaced globally by 2030 due to technological advancements. According to the WEF (2017b) and the ILO (2023), approximately 41% of the work activities in South Africa are susceptible to automation. This indicates that these tasks could, in principle, be performed by current or near-future technologies. This estimate is based on a task-level analysis that identified the specific activities comprising jobs, such as routine data entry, predictable machine operation, or repetitive manual tasks. The analysis assessed their potential to be executed by technologies, including AI, robotics, and software automation (WEF, 2017b).

Ramdoo (2018) also reported that an estimated 41% of all employment activities are at risk of being replaced by automation in SA. If automation is implemented without a proper initiative for reskilling, there is likely to be social upheaval due to the disruption that automation can bring (Valiani, 2018). This is particularly true in mining communities where mining is the main source of livelihoods. Figure 4 shows the main occupations in the Australian mining sector (Australian Government Department of Employment, 2014). Most mining jobs are related to blasting and operating machines, including driving trucks and drilling (Ramdoo, 2018). This routine work is susceptible to automation; thus, this innovation is likely to make these jobs redundant (Sam-Aggrey, 2020).

Figure 4 Main employing occupations in the mining industry (×1,000) (see online version for colours)



Source: Australian Government Department of Employment (2014)

The study by PwC et al. (2023) projected that by 2030, approximately 30% of the mining jobs in South Africa may be at risk due to automation, robotics, and other 4IR technologies. This estimate does not imply that 30% of the mining jobs will be eliminated, but rather that these roles are at risk of significant transformation or partial displacement. The quantification was based on a task-level analysis of mining work, where individual job components were assessed for their susceptibility to automation. Roles involving repetitive, predictable, or mechanisable tasks, such as drill-and-blast operations, routine material handling, and certain monitoring functions, were identified as most vulnerable. By aggregating the share of such tasks across all mining occupations, the study estimated that up to 30% of mining jobs contain activities that could potentially be automated by 2030 (PwC et al., 2023).

The study by PwC (2023) highlighted that workers are becoming concerned about their job security. The threat that 4IR technologies present to the job security of many mine workers has resulted in resistance to their adoption by mining unions. The unions have concerns that their collective bargaining power will be expunged by the adoption of 4IR. According to Karolia-Hussain and Fourie (2021), the power of mine unions could be diminished as there will be fewer numbers of workers employed in the sector. Most of those still employed in the sector will be non-permanent contractors working remotely. The introduction of automation in mines is therefore likely to lead to strike action due to protests by mine workers backed by unions. They will fear being substituted by machines and the resultant job losses (Karolia-Hussain and Fourie, 2021).

There is also a fear that the adoption of 4IR technologies in mining will negatively impact local empowerment commitments by mining operations. In addition, the adoption of automation in mines will likely have a negative socio-economic impact on the local mining communities (Lund et al., 2024). The reduction in job opportunities for the locals from mining operations will resultantly lead to a decline in the disposable income that is available for spending in local communities, negatively impacting the livelihoods of these communities (Xin and Ye, 2024). This is because mining will now mainly employ fewer high-earning skilled personnel, and this will, in turn, result in increased levels of inequality in these communities (Paredes and Fleming-Munoz, 2021).

The study done by Cosbey et al. (2016) found that mining automation will reduce mining's contribution to developed countries' GDPs by between 9 and 20%. The resultant reduction in developing countries will be between 13 and 31%. This will mainly be driven by a reduction in personal income, as mining will employ fewer workers. In addition, automation-associated drops in local procurements will also contribute to the decline of mining's contribution to the GDP (Cosbey et al., 2016). The debate now becomes whether the purported fiscal benefits that are generated from taxation, equity stakes, and royalties will be adequate to compensate for the costs incurred due to automation (job losses, reduction in local procurement, etc.). As already outlined in the studies above that show the automation-induced reduction in mining's contributions to developing countries' GDPs, it is unlikely that the purported benefits of the improved profitability of the mining companies will outweigh the outlined losses experienced by the host countries and local communities because of automation.

Another potential negative impact of adopting 4IR technologies in mining is their capacity to shorten the life of mines (LOMs). Automation, advanced analytics, and digital optimisation could improve productivity and enable the economic extraction of lower-grade ore, which would previously have been considered uneconomical. However, these same efficiency gains often increase extraction rates and throughput, thereby accelerating the depletion of finite mineral resources and causing deposits to be exhausted sooner than they would have been under traditional mining methods (Sam-Aggrey, 2020). A shortened LOM can have severe socio-economic consequences for mining-dependent communities, particularly small and rural settlements that rely heavily on mining for employment and local economic activity. Furthermore, reduced mine lifespans may constrain the ability of mining companies to deliver fully on long-term environmental rehabilitation and social development commitments. This will increase the risk of post-closure socio-economic decline (Attarbo, 2025).

6 Integrated policy and risk framework for Mining 4.0

These implications indicate that the adoption of 4IR technologies in mining must be accompanied by targeted and coordinated policy interventions to ensure that technological advancement translates into inclusive socio-economic benefits for host communities. This study highlights the following priority policy recommendations in the context of a developing country such as South Africa:

1. The establishment of a just transition fund to support automation and green projects, specifically earmarked for worker re-skilling, income protection, and economic diversification in mining-dependent communities (Lööw, 2020; Tamasiga, 2025).
2. The creation of an independent regulatory body to oversee autonomous decision-making systems, data governance, and algorithmic accountability, ensuring transparency, fairness, and compliance with labour and privacy regulations (UK Department for Science, Innovation & Technology, 2020; Corrigan and Laye, 2022).
3. The implementation of a national mining-focused digital skills and training strategy aimed at improving digital fluency and technical competencies across all occupational levels, including mineworkers, supervisors, and local suppliers (Cosbey et al., 2016; Lund et al., 2024).
4. The strengthening of regulatory frameworks, including labour laws, occupational health and safety standards, and corporate social responsibility requirements, to ensure they remain responsive to the operational realities introduced by 4IR technologies (Karolia-Hussain and Fourie, 2021; WEF, 2021).
5. Targeted support for local suppliers and SMEs to enable their participation in technologically advanced mining value chains through skills development, access to finance, and technology transfer initiatives (Lund et al., 2024; Lenzi and Panzera, 2025).

Collectively, these measures emphasise that the successful integration of 4IR technologies in mining depends not only on technological readiness but also on proactive governance, inclusive skills development, and community-centred development strategies. This study synthesises the prior empirical and conceptual research into an integrated analytical framework to consolidate these insights and address the fragmented treatment of Mining 4.0 risks in the existing literature. Table 4 brings together evidence of the core 4IR technologies, the underlying risk mechanisms, the empirical indicators, and the representative South African and international case studies. The framework provides a coherent synthesis of the key patterns and contextual differences identified across the reviewed literature. It explicitly links technological adoption pathways to workforce, governance, cybersecurity, and environmental risk dimensions.

Table 4 Conceptual framework linking 4IR technologies to key risk dimensions in mining

Risk dimension	*Core 4IR technologies*	*Empirical evidence (quantitative/case-based)*	*Key case studies (geographic location)*	*Conceptual insight/mechanism*	*Key references*
Workforce displacement and skills polarisation	Automation, autonomous haulage, AI-driven scheduling, and remote operations.	• Up to 30% of mining jobs at risk in SA by 2030 (task-based analysis). • 41% of work activities in SA potentially automatable.	• Platinum sector (SA) • Coal-to-renewables transition (Komati, SA) • Autonomous haulage (Australia and Chile).	Automation replaces task bundles, not entire occupations, producing direct, indirect, and transitional job losses. Skills mismatch amplifies exclusion in developing contexts.	Cosbey et al. (2016), WEF (2017a), PwC et al. (2023), ILO (2023)
Environmental and occupational health (OHS) risks	Smart sensors, nanotechnology, algorithmic management platforms, remote operations centres, and autonomous systems.	• Higher energy consumption, electronic waste, OHS risks (e.g., tampered with/ malfunctioning gas sensors and ventilation failures). • Psychosocial risks: stress, anxiety, and reduced autonomy from constant monitoring/remote work.	• SA underground gas/ventilation risk scenarios, SA and global algorithmic management studies, and mining sites with drone deployments.	4IR can introduce new OHS hazards (cyber-induced or operational) and environmental externalities (energy use, e-waste). Algorithmic governance impacts worker well-being (fairness, autonomy, and mental health).	Lööw et al. (2019), Sam Aggrey (2020), Li et al. (2023), OECD (2025)
Ethical and algorithmic governance risks	AI decision-support systems, surveillance drones, and algorithmic management.	• Evidence of algorithmic bias, worker stress, and reduced autonomy. • Documented misuse of surveillance technologies.	• Drone surveillance (global/SA context). • Algorithmic management (EU, cross-industry).	Delegation of authority to algorithms shifts responsibility without eliminating risk, raising accountability and fairness concerns.	Candrian and Scherer (2022), ILO (2022), Onifade et al. (2024), OECD (2025), Bandara et al. (2025)
Cybersecurity and critical infrastructure vulnerability	IoT sensors, autonomous systems, and cloud-based OT/ICS networks.	• 88% of SA firms breached in 1 year. • Repeated incidents (2–5+ breaches annually). • Rio Tinto ransomware (global).	• Sibanye-Stillwater cyberattack (SA). • Copper Mountain shutdown (Canada).	Digital interconnectivity amplifies cyber-physical risks, converting operational failures into national security concerns.	Sun et al. (2019), CSIR (2024), CISA (2024), Zvarivadza et al. (2024), WEF (2025), Brancati et al. (2025)
LOM shortening and resource depletion	Advanced analytics, automated drilling, and optimisation algorithms.	• Evidence linking automation to accelerated extraction rates. • Shortened mine life observed in productivity-driven operations.	• High-throughput mechanised mines (Australia, Chile). • Resource depletion risks in SA's platinum sector.	Efficiency gains compress extraction timelines, intensifying post-closure socio-economic risks.	Sam-Aggrey (2020), WEF (2020), Attarbo (2025), Lenzi and Panzera (2025)
Community and local economic disruption	Digitised supply chains, remote-control centres, and automation.	• GDP contribution decline of 13%–31% in developing economies due to automation.	• Mining-dependent communities (SA, Chile). • Supplier exclusion in digitised procurement.	Automation weakens local employment multipliers and undermines the social licence to operate without compensatory policy mechanisms.	Cosbey et al. (2016), Mnwana and Bowman (2018), Lund et al. (2024), Xin and Ye (2024)

7 Conclusions

This review makes a distinct contribution to the body of literature by moving beyond the predominantly techno-optimistic Mining 4.0 literature. It does so by systematically consolidating the negative socio-economic, ethical, governance, and operational risks associated with 4IR adoption in South Africa's mining sector. The study integrates mining-specific and cross-sectoral evidence and clarifies how automation, digital surveillance, AI-driven decision-making, and cybersecurity interdependencies generate compound risks that are often under-represented in policy and industry discourse.

The study identifies several priority actions that should accompany the adoption of 4IR technologies in mining to translate these insights into practice. Just-transition mechanisms are required to fund worker reskilling, redeployment, and economic diversification in mining-dependent communities. Stronger regulatory and ethical oversight is needed to govern autonomous systems, algorithmic decision-making, and workplace data use. A coordinated national strategy is also required to build digital fluency and specialised Mining 4.0 skills across the workforce. In parallel, labour legislation, occupational health and safety standards, and corporate social responsibility frameworks must be updated to reflect automation and digitalisation. Finally, targeted support for local suppliers and small enterprises is essential to prevent exclusion from technology-intensive mining value chains and to ensure broader distribution of Mining 4.0's benefits.

The limitations of the study arise from its reliance on secondary and cross sector sources due to the scarcity of systematically reported mining case studies. Future research work should prioritise longitudinal quasi experimental studies on worker/community outcomes and causal safety evaluations comparing autonomous vs. conventional operations. It should also prioritise the cyber resilience effectiveness of secure by design mandates and resource depletion/LOM simulations calibrated to South African ore bodies.

Declarations

No potential conflict of interest was reported by the author(s).

References

Alexander, R. (2022) *Ranking of Barriers to 4IR Adoption in South African Mines: SARChI Industrial Development*, Working Paper Series WP 2021-08d, University of Johannesburg, Johannesburg.

Anglo American Platinum (2023) *Integrated Annual Report*, Anglo American, Johannesburg.

Attarbo, E.A. (2025) 'Implementing autonomous haulage trucks in mining: safety benefits and management challenges', *World Journal of Advanced Engineering Technology and Sciences*, Vol. 17, No. 2, pp.329–335.

Australian Government Department of Employment (2014) *Industry Outlook: Mining*, Microsoft Word – 2014 Mining Industry Employment Outlook.docx (accessed 6 November 2025).

Bandara, R., Biswas, K., Akter, S., Shafique, S. and Rahman, M. (2025) 'Addressing algorithmic bias in AI-driven HRM systems: implications for strategic HRM effectiveness', *Human Resource Management Journal*, Vol. 35, pp.1047–1063, https://doi.org/10.1111/1748-8583.12609.

Barbudhe, V. (2024) 'Cyber attacks on UAV networks: a comprehensive survey', *Review of Computer Engineering Research*, Vol. 11, No. 1, pp.45–57.

BDO (2025) *Annual Mining Report: Transforming the Industry with Sustainability Innovation and Critical Minerals*, London.

Belur, R.D. (2024) *The Use of 4IR Technology in Accelerating Net Zero Transition in the South African Mining Industry*, University of Witwatersrand, Johannesburg.

Bonsu, J., van Dyk, W., Franzidis, J-P., Petersen, F. and Isafiade, A. (2017) 'A systemic study of mining accident causality: an analysis of 91 mining accidents from a platinum mine in South Africa', *Journal of the Southern African Institute of Mining and Metallurgy*, January, Vol. 117, pp.59–66.

Brancati, F., Mongelli, D., Mariotti, F. and Lollini, P. (2025) 'A cybersecurity risk assessment methodology for industrial automation control systems', *International Journal of Information Security*, Vol. 24, No. 76, pp.10–21.

Candrian, C. and Scherer, A. (2022) 'Rise of the machines: delegating decisions to autonomous AI', *Computers in Human Behavior*, Vol. 134, No. 107308, pp.1–16.

Caruana, L. (2024) 'Implications of an autonomous truck incident', *Australian Mining Monthly*, 31 January [online] https://www.miningmonthly.com/technology/news-articles/1464235/implications-autonomous-truck-incident (accessed 11 June 2025).

CMIC Global (2025) *Mining Industry Trends 2025: New Developments in the Mining Industry*, CMIC, Totonto.

Computer Security Resource Centre (2023) *Guide to Operational Technology (OT) Security*, National Institute of Standards and Technology, US Department of Commerce, Gaithersburg.

Copper Mountain Mining Company (2022) *Copper Mountain Mining Subject to Ransomware Attack and Implements Risk Management Systems and Protocols*, Canada, Vancouver, BC.

Corrigan, C. and Laye, P. (2022) *The Use of AI in the Mining Industry – Insights and Ethical Considerations*, Technical University of Munich, Institute for Ethics in Artificial Intelligence, Munich.

Cosbey, A., Mann, H., Maennling, N., Toledano, P., Geipel, J. and Brauch, D. (2016) *Mining a Mirage? Reassessing the Shared-Value Paradigm in Light of the Technological Advances in the Mining Sector*, International Institute for Sustainable Development, Winnipeg, Manitoba.

Costello, F. and Watts, P. (2014) *Surprisingly Rational: Probability Theory Plus Noise Explains biaSes in Judgement*, arXiv:1211.0501[physics.data-an], https://doi.org/10.48550/arXiv.1211.0501.

Council for Scientific and Industrial Research (CSIR) (2024) *Data Breaches in South Africa: Survey Report*, Pretoria.

Cybersecurity and Infrastructure Security Agency (CISA) (2024) *IoT in Connected Communities: Risk and Mitigation Measures*, Washington [online] https://www.cisa.gov/sites/default/files/2024-12/PDM24069_CCI_IoT_Device_Risk_and_Mitigation_Infographic_Final_508.pdf (accessed 15 July 2025).

Cybersecurity and Infrastructure Security Agency (CISA) (2025) *China State-Sponsored Cyber Threat: Advisories* [online] https://www.cisa.gov/topics/cyber-threats-and-advisories/nation-state-cyber-actors/china/publications (accessed 12 January 2026).

Datta, P.M. (Ed.) (2022) '4IR operations, technology, and sustainability', in *Global Technology Management 4.0*, pp.189–198, Springer, Cham.

Ediriweera, A. and Wiewiora, A. (2021) 'Barriers and enablers of technology adoption in the mining industry', *Resources Policy*, Vol. 73, pp.1–14, https://doi.org/10.1016/j.resourpol.2021.102188.

Erasmus, D. (2024) timesmedia2.pressreader.com [online] https://timesmedia2.pressreader.com/article/281552295711995 (accessed 5 January 2026).

Florida, L., Cowls, J., Beltrametti, M., Chatila, R., Chazerand, P., Dignum, V., Luetge, C., Madelin, R., Pagallo, U., Rossi, F., Schafer, B., Valcke, P. and Vayena, E. (2018) 'An ethical framework for a good AI society: opportunities, risks, principles, and recommendations', *Minds and Machines*, Vol. 28, No. 4, pp.689–707, https://doi.org/10.1007/s11023-018-9482-5.

García-Ruiz, P. and Rocchi, M. (2025) 'Can work be meaningful under algorithmic management? A MacIntyrean perspective', *Business Ethics Quarterly*, Vol. 28, No. 1, pp.1–28, https://doi.org/10.1017/beq.2025.5.

Ghosh, R. (2020) *Applications, Promises and Challenges of Artificial Intelligence in Mining Industry: A Review*, Department of Mining Engineering, Indian Institute of Engineering Science and Technology, West Bengal, India.

Girma, A. and Brown, K. (2024) 'Security analysis of drone communication methods', in Latifi, S. (Ed.): *ITNG 2024: 21st International Conference on Information Technology-New Generations. ITNG 2024. Advances in Intelligent Systems and Computing*, Vol. 1456, pp.125–131, https://doi.org/10.1007/978-3-031-56599-1_18.

Global Data (2024) *Mine-Site Technology Adoption Survey, 2024 Update*, Global Data, London.

Global Data (2025) *Mine-Site Technology Adoption Survey, 2025*, Global Data [online] https://www.globaldata.com/store/report/mine-site-technology-adoption-survey-analysis/ (accessed 10 January 2026).

Global Mining Guidelines Group (2024) *Guideline for the Implementation of Autonomous Systems in Mining, Châteauguay*, GMG, Quebec.

Gonese, D. and Ngepah, N.N. (2024) 'Fourth industrial revolution technologies and sectoral employment in South Africa', *Cogent Social Sciences*, Vol. 10, No. 1, pp.1–19.

Grand View Research (2025) *Mining Automation Market Size & Trends*, Grand View Research, Inc., San Francisco.

Hewapathirana, G.I. and Almasri, F. (2021) 'Talent development challenges and opportunities in the 4th industrial revolution: a boundaryless career theory perspective', in Al Mawali, N.A.L. (Ed.): *Fourth Industrial Revolution and Business Dynamics*, pp.287–320, Palgrave Macmillan, Singapore.

Horberry, T., Burgess-Limerick, R., Cook, T. and Steiner, L. (2016) 'Improving mining equipment safety through human-centered design', *Ergonomics in Design: Quarterly of Human Factors Applications*, Vol. 24, No. 3, pp.1–6, https://doi.org/10.1177/1064804616636299.

Indurjeeth, A. (2021) *A Critical Analysis of Capital Expenditure in the Mining Industry*, University of Johannesburg, Johannesburg.

Institute of Electrical and Electronics Engineers (2023) *What Self-Driving Cars Tell us about AI Risks* [online] https://spectrum.ieee.org/self-driving-cars-2662494269 (accessed 6 June 2025).

International Energy Agency (IEA) (2024) *Accelerating just Transitions for the Coal Sector*, Paris.

International Labour Organisation (ILO) (2022) *The Algorithmic Management of Work and its Implications in Different Context*, Geneva.

International Labour Organisation (ILO) (2023) *Skills Demand and Supply in South Africa's Digital Economy: A Focus on Youth not in Employment, Education or Training*, Geneva.

International Monetary Fund (IMF) (2024) *Regulating AI: Challenges and Policy Options*, Working Paper, Washington, DC.

International Renewable Energy Agency (IRENA) (2023) *Socio-economic Footprint of the Energy Transition: South Africa*, Abu Dhabi.

International Renewable Energy Agency (IRENA) (2023) *Socio-economic Footprint of the Energy Transition: South Africa*, Abu Dhabi.

Johannesburg Stock Exchange (JSE) (2024) *Sibanye-Stillwater Reports a Cybersecurity Attack: SENS Announcement*, Johannesburg.

Jones, L.B., Thornton, J. and De Silva, D. (2025) 'Limitations of risk-based artificial intelligence regulation: a structuration theory approach', *Discover Artificial Intelligence*, Vol. 5, No. 14, https://doi.org/10.1007/s44163-025-00233-9.

Karolia-Hussain, F. and Fourie, E. (2021) 'The relevance and impact of South African labour law in the mining sector: a fourth industrial revolution perspective', *OBITER*, Vol. 42, No. 3, pp.445–469.

Khoza, N.G. (2025) 'The fourth industrial revolution (4IR) readiness in South Africa's public sector: pathways to achieving SDGs', *International Journal of Development and Sustainability*, Vol. 14, No. 1, pp.117–136.

Kjaer, P.F. and Vetterlein, A. (2018) 'Regulatory governance: rules, resistance and responsibility', *Contemporary Politics*, Vol. 24, No. 5, pp.497–506.

Labuschagne, H. (2025) *World Bank Approves $497 Million in Financing to Lower South Africa's Greenhouse Gas Emissions and Support a Just Transition* [online] https://www.worldbank.org/en/news/press-release/2022/11/04/world-bank-approves-497-million-in-financing-to-lower-south-africa-s-greenhouse-gas-emissions-and-support-a-just-transit (accessed 8 January 2026).

Lacoursiere, M.S. (2025) 'The social license to automate in the mining industry', *Mineral Economics*, Vol. 38, pp.413–424, https://doi.org/10.1007/s13563-025-00494-x.

Lenzi, C. and Panzera, E. (2025) 'Income and wage inequalities from automation. A European perspective', *Review of Regional Research*, Vol. 45, pp.395–420, https://doi.org/10.1007/s10037-025-00225-3.

Li, X., Wei, Q., Wu, Z. and Guo, W. (2023) 'Finding taint-style vulnerabilities in Lua application of IoT firmware with progressive static analysis', *Applied Sciences*, Vol. 13, No. 17, p.9710.

Lööw, J. (2020) *'Soft' Questions in a 'Hard' Industry?*, PhD thesis, Luleå: Luleå University of Technology [online] https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1448655&dswid=-722 (accessed 8 October 2025).

Lööw, J. (2021) 'Understanding technology in mining and its effect on the work environment', *Mineral Economics*, Vol. 10, No. 7, pp.1–12.

Lumadi, V.W. and Nyasha, S. (2024) 'Technology and growth in the South African mining industry: an assessment of critical success factors and challenges', *The Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 124, No. 4, pp.163–171.

Lund, E., Pekkari, A., Johansson, J. and Lööw, J. (2024) 'Mining 4.0 and its effects on work environment, competence, organisation and society – a scoping review', *Mineral Economics*, Vol. 37, No. 1, pp.827–840.

Mallreddy, S.R. and Vasa, Y. (2022) 'Autonomous systems in software engineering: reducing human error in continuous deployment through robotics and AI', *Natural Volatiles & Essential Oils*, Vol. 9, No. 1, pp.13653–13660.

Mandela Mining Precinct (2022) *SATCAP WP2.2 Research Findings Report: Skills Assessment for Technology Adoption Preparedness*, University of Witwatersrand, Johannesburg.

Manyuchi, A.E., Mbohwa, C. and Muzenda, E. (2020) 'The fourth industrial revolution (4IR) and the mining industry in Sub-Saharan Africa: challenges and opportunities', *South African Journal of Industrial Engineering*, Vol. 31, No. 3, pp.1–10.

McKinsey & Company (2014) *The Rising Strategic Risks of Cyberattacks*, Washington.

McKinsey & Company (2025) *The Growth of the Global Lighthouse Network Showcases the Opportunities for Fourth Industrial Revolution Technologies to make a Positive Impact for People and the Planet* [online] https://www.mckinsey.com/capabilities/operations/our-insights/the-continuing-evolution-of-the-global-lighthouse-network (accessed 10 January 2026).

Memon, K.R. and Ooi, S.K. (2021) 'The dark side of industrial revolution 4.0-implications and suggestions', *Academy of Entrepreneurship Journal*, Vol. 27, No. 2, pp.1–19.

Microsoft Copilot (2025) *AI-Generated Image Illustrating South Africa's Transition from Coal to Renewable Energy and Associated Job Displacement*, Micrrosoft, Cambridge.

Mine Health and Safety Council (MHSC) (2021) *Compendium of Research Project Summaries on Human Factors and Behavioural Safety – 1995 to 2014*, Johannesburg.

Mnwana, S. and Bowman, A. (2018) 'Mine mechanisation and distributional conflict in rural South Africa', *Resources Policy*, Vol. 59, pp.227–237, https://doi.org/10.1016/j.resourpol.2018.07.008.

Molobi, S.M. (2024) *Evaluating the Adoption of Fourth Industrial Revolution (4IR) Related Technologies by the Department of Home Affairs*, University of the Witwatersrand, Johannesburg.

Nyagadza, B., Pashapa, R., Chare, A., Mazuruse, G. and Hove, P.K. (2021) 'Digital technologies, Fourth Industrial Revolution (4IR) & global value chains (GVCs) nexus with emerging economies' future industrial innovation dynamics', *Cogent Economics & Finance*, Vol. 9, No. 1, pp.1–14.

Obagbuwa, O. and Munzhelele, F. (2024) 'Green investment in South Africa: a perception of overinvestment or underinvestment in energy and mining firms', *Investment Management and Financial Innovations*, Vol. 21,No. 1, pp.229–243.

OECD (2025) *Algorithmic Management in the Workplace: New Evidence from an OECD Employer Survey*, OECD Publishing, Paris.

Olaleye, S., Adebayo, A., Odeyinka, H. and Alabi, O. (2022) 'Challenges of Industry 4.0 adoption: evidence from developing economies', *Engineering Proceedings*, Vol. 6, No. 6, p.136.

Onifade, M., Adebisi, J.A. and Zvarivadza, T. (2024) 'Recent advances in blockchain technology: prospects, applications and constraints in the minerals industry', *International Journal of Mining, Reclamation and Environment*, Vol. 38, No. 7, pp.497–533.

Opray, M. (2016) 'Revealed: Rio Tinto's plan to use drones to monitor workers' private lives', *The Guardian*, 8 December [online] https://www.theguardian.com/world/2016/dec/08/revealedrio-tinto-surveillance-station-plans-to-use-drones-to-monitors-staffs-private-lives?utm_source=chatgpt.com (accessed 10 June 2025).

Pakdel, J. and Erol, I. (2025) 'Scrutinizing challenges to adopting digital technologies in the mining industry: a systematic review through PRISMA and bibliometric analysis', *Resources Policy*, Vol. 109, No. 105713, pp.1–13.

Paredes, D. and Fleming-Munoz, D. (2021) 'Automation and robotics in mining: jobs, income and inequality implications', *The Extractive Industries and Society*, Vol. 8, No. 1, pp.189–193.

Patterson, J. (2009) *Human Error in Mining: A Multivariable Analysis of Mining Accidents/Incidents in Queensland, Australia and the United States of America using the Human Factors Analysis and Classification System Framework*, Clemson University, Clemson, South Carolina.

Power, D.J., Heavin, C. and O'Connor, Y. (2021) 'Balancing privacy rights and surveillance analytics: a decision process guide', *Journal of Business Analytics*, Vol. 4, No. 2, pp.155–170.

PricewaterhouseCoopers (PwC) (2023) *Ten Insights into 4IR 2023: The State of Digital Transformation in the South African Mining Industry*, Mineral Council South Africa, Johannesburg.

PricewaterhouseCoopers, The Mineral Council South Africa & the Mandela Mining Precinct (PwC, MCSA & MMP) (2023) *The State of Digital Transformation in the South African Mining Industry*, Johannesburg.

Ramdoo, I. (2018) *Skills Development in The Mining Sector: Making More Strategic Use of Local Content Strategies*, United Nations Trade and Development, Geneva [online] https://unctad.org/news/skills-development-mining-sector-making-more-strategic-use-local-content (accessed 19 June 2025).

Ruiz-del-Solar, J. (2025) 'The road to the mine of the future: autonomous collaborative mining', *Mining*, Vol. 5, No. 25, pp.1–20, https://doi.org/10.3390/mining5020025.

SA Government (2014) *Protection of Personal Information Act 4 of 2013*, South African Government, Cape Town.

SA Parliament (2025) *Media Statement: Electricity and Energy Committee Engages with Stakeholders on the Decommissioning of Komati Power Station*, Parliament of the Republic of South Africa, Cape Town [online] https://www.parliament.gov.za/press-releases/media-statement-electricity-and-energy-committee-engages-stakeholders-decommissioning-komati-power-station (accessed 20 June 2025).

Sam-Aggrey, H. (2020) 'Assessment of the impacts of new mining technologies: recommendations on the way forward', *WIT Transactions on Ecology and the Environment*, Vol. 245, pp.177–187, DOI: 10.2495/EID200171.

Shrivastava, P. (2025) 'Understanding acceptance and resistance toward generative AI technologies: a multi-theoretical framework integrating functional, risk, and sociolegal factors', *Frontiers in Artificial Intelligence*, Vol. 8, pp.1–10, https://doi.org/10.3389/frai.2025.1565927.

Sibanye-Stillwater (2023) *Integrated Annual Report*, Johannesburg.

Sithole, M.A. (2024) *Drivers and Barriers to the Adoption of Digital Technologies in the Mining Industry in a Developing Country*, University of Pretoria, Pretoria.

Smit, A.C. and Mji, A. (2012) 'Assessment of numeracy levels of mine workers in South African chrome mines', *Numeracy*, Vol. 5, No. 2, pp.1–10.

Smith, K. and Sepasgozar, S. (2022) 'Governance, standards and regulation: what construction and mining need to commit to Industry 4.0', *MDPI-Buildings*, Vol. 12, No. 1064, pp.1–20.

South Africa (SA) Department of Higher Education and Training (2024) *Identification of Skills Gaps in South Africa*, Department of Higher Education and Training, Pretoria.

Stander, H-M. and Broadhurst, J.L. (2021) 'Understanding the opportunities, barriers, and enablers for the commercialization and transfer of technologies for mine waste valorization: a case study of coal processing wastes in South Africa', *MDPI-Resources*, Vol. 10, No. 35, pp.1–15.

Steenkamp, D., Pretorius, J-H., Roos, P. and Hanekom, J. (2025) 'Codera: mining patent data shows innovation is lagging' [online] https://www.businessday.co.za/bd/opinion/2025-04-24-codera-mining-patent-data-shows-innovation-is-lagging/ (accessed 14 July 2025).

Sun, X., Ng, D., Ding, Z., Xu, Y. and Zhong, Z. (2019) 'Physical layer security in UAV systems: challenges and opportunities', *IEEE Wireless Communications*, Vol. 26, No. 5, pp.1–17, https://doi.org/10.1109/MWC.001.1900028.

Tamasiga, P. (2025) *Workforce Transition in South Africa's just Energy Transition: An Analysis of Needs, Policy Gaps and Socioeconomic Implications*, Stiftung Wissenchaft und Politik, Berlin.

Tilo, D. (2023) *Stolen Rio Tinto Employee Data from Cyber-Attack Uploaded on Dark Web: Reports*, Human Resources Director (HRD), Australia.

Trotta, A., Ziosi, M. and Lomonaco, V. (2023) 'The future of ethics in AI: challenges and opportunities', *AI & Society*, March, Vol. 38, No. 2, pp.439–441, https://doi.org/10.1007/s00146-023-01644-x.

Tsiligiris, V. and Bowyer, D. (2021) 'Exploring the impact of 4IR on skills and personal qualities for future accountants: a proposed conceptual framework for university accounting education', *Accounting Education*, Vol. 30, No. 6, pp.621–649.

Tunnicliffe, A. (2024) *Cybersecurity: Getting IT Right, or Not?*, Mining Technology, New York [online] https://mine.nridigital.com/mine_australia_sep24/cybersecurity-it-ot (accessed 12 June 2025).

UK Department for Science, Innovation & Technology (2020) *Review into Bias in Algorithmic Decision-Making*, UK Government, London [online] https://www.gov.uk/government/publications/cdei-publishes-review-into-bias-in-algorithmic-decision-making (accessed 13 June 2025).

Valiani, S. (2018) *The Future of Mining in South Africa: Sunset or Sunrise?*, Mapungubwe Institute for Strategic, Johannesburg [online] https://www.jstor.org/stable/j.ctvgc60w8 (accessed 11 June 2025).

Vangu, G.M. (2022) 'The use of drones in mining operations', *Revista Minelor – Mining Revue*, Vol. 28, No. 3, pp.73–82.

Wills, N. (2025) *Just Energy Transition: How Disused Coal Mines could become Sites of Job Creation*, Cape Town, econ3x3.org [online] https://www.econ3x3.org/article/just-energy-transition-how-disused-coal-mines-could-become-sites-job-creation (accessed 14 August 2025).

World Bank (2022) *World Bank Approves a497 Million in Financing to Lower South Africa's Greenhouse Gas Emissions and Support a Just Transition* [online] https://www.worldbank.org/en/news/press-release/2022/11/04/world-bank-approves-497-million-in-financing-to-lower-south-africa-s-greenhouse-gas-emissions-and-support-a-just-transit? (accessed 8 January 2026).

World Economic Forum (WEF) (2017a) *Digital Transformation Initiative, Mining and Metals Industry*, Geneva.

World Economic Forum (WEF) (2017b) *The Future of Jobs and Skills in Africa: Preparing the Region for the Fourth Industrial Revolution*. Geneva.

World Economic Forum (WEF) (2020) *The Future of Jobs Report*, Geneva.

World Economic Forum (WEF) (2021) *Towards a Data Economy: An Enabling Framework*, (White Paper), Geneva,

World Economic Forum (WEF) (2023) *Innovative Approaches for Unlocking R&D Funding in Africa* [online] https://www.weforum.org/stories/2023/11/innovative-approaches-for-unlocking-research-and-development-funding-in-africa/ (accessed 10 August 2025).

World Economic Forum (WEF) (2025) *Global Cybersecurity*, Geneva [online] https://www.weforum.org/publications/global-cybersecurity-outlook-2025/ (accessed 10 July 2025).

Xin, B. and Ye, X. (2024) 'Robotics applications, inclusive employment and income disparity', *Technology in Society*, Vol. 78, No. 102621, pp.1–15.

Zayid, H., Alzubi, A., Berberoglu, A. and Khadem, A. (2024) 'How do algorithmic management practices affect workforce well-being? A parallel moderated mediation model', *Behavioral Sciences*, Vol. 14, No. 12, p.1123.

Zvarivadza, T., Onifade, M., Dayo-Olupona, O. and Said, K.O. (2024) 'On the impact of industrial internet of things (IIoT) – mining sector perspectives', *International Journal of Mining, Reclamation and Environment*, Vol. 38, No. 10, pp.771–809.