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Evidence-Based Research on the Impact of New Technologies in the Mining Industry

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Executive Summary

The global mining sector is experiencing a profound transformation driven by the increasing demand for critical minerals essential to the energy and digital transitions, alongside mounting pressures from investors, consumers, and civil society for more sustainable and equitable mining practices. Accompanying and supporting this transformation, new technologies are being rapidly integrated into large-scale mining operations, significantly impacting labour markets, supply chains, and host communities. This report provides an analysis of technology adoption and their associated impacts, drawing on case studies from six large-scale mining operations in six different countries: Australia, Burkina Faso, Côte d'Ivoire, the Democratic Republic of the Congo (DRC), Guinea, and South Africa.

Key Findings

The findings outlined here come from both qualitative information and quantitative data gathered from mining companies:

- **accelerated technological adoption**: Mining companies are increasingly integrating advanced technologies such as artificial intelligence (AI), autonomous machinery, and data analytics. This trend enhances operational efficiency and safety, particularly in underground mining, but varies by region due to differences in resources and infrastructure.
- **disparities between economies**: Advanced mining economies like Australia and South Africa are leading in technology adoption due to better financial and infrastructural resources. In contrast, emerging mining economies, including Burkina Faso and the DRC, face challenges such as high costs and limited connectivity, which slow the pace of adoption. However, declining technology costs may eventually improve accessibility in these regions.
- **labour market shifts**: Adoption of new technologies is reshaping the labour market by reducing demand for low-skilled jobs and increasing the need for specialized skills in information technologies (IT), data management, and engineering. While automation reduces the demand for certain roles, it also creates new, higher-paid opportunities. However, these jobs require qualifications that are often insufficiently available locally, particularly in developing countries.
- **varied impacts on job**: The effect of technological adoption on employment varies widely across countries examined in this report. Some companies have reduced their workforces, while others have redeployed or retrained employees to minimize job losses. The most disruptive technologies are still in the early stages of adoption in most countries examined; therefore, the full impact on employment is yet to be assessed.
- **gendered job opportunities**: Technologies are opening up job opportunities for women, but their uptake is limited by the underrepresentation of women in science, technology, engineering, and mathematics fields. Targeted policies and initiatives are needed to address this imbalance and increase women's participation in the jobs needed for the digitalization of mining.

- **indirect and local benefits**: Technology adoption is generating indirect job opportunities and new business ventures, particularly in digital services. However, in emerging economies, local benefits are limited due to the reliance on imported technologies and lack of local manufacturing capacity.
- **need for proactive measures**: Both mining companies and governments are taking steps to address the challenges posed by the deployment of new technologies, but further action is needed. This includes improving workforce skills and capabilities, fostering local technological innovation, and enhancing community engagement to ensure broad-based benefits.

Policy Recommendations

To navigate the ongoing transformation in the mining sector and ensure that its benefits are broadly shared, governments and companies must adopt forward-looking, data-driven strategies. Key recommendations include the following:

- monitor labour dynamics: implement systems to track the impact of technologies on jobs and skills, and the skills requirements of the mining sector, allowing for timely support and adaptation;
- adapt training programs: align educational and vocational training with the emerging needs of the mining sector, focusing on digital and technical skills;
- invest in infrastructure: enhance connectivity and digital infrastructure, especially in emerging economies, to facilitate wider technology adoption;
- support local content: encourage local production and service provision through content policies and technology hubs;
- engage communities: foster community involvement in technology adoption, ensuring local benefits and addressing potential social impacts.

This report underscores the need for a collaborative approach between governments, industry, and communities to manage the complex dynamics of technological change in the mining sector. By proactively addressing the challenges and seizing the opportunities presented by new technologies, stakeholders can ensure that the benefits of mining's digital transformation are shared widely and equitably.

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1.0 Background, Purpose, and Scope of the Study

1.1 Introduction

In recent years, the mining industry has undergone significant changes with the adoption of new technologies. Building on the findings of the 2018 Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) research project New Tech New Deal (Ramdoo, 2019), which explored the potential impacts of emerging technologies on the sector, this report takes a step further by empirically analyzing the real impacts of these technologies, notably on labour markets, supply chains, and host communities across the mining value chain.

Focusing on case studies from six countries—Australia, Burkina Faso, Côte d'Ivoire, the Democratic Republic of the Congo (DRC), Guinea, and South Africa—this report highlights how the integration of advanced technologies like AI and autonomous machinery is reshaping the industry. While these advancements are improving efficiency and safety, particularly in advanced economies, they are also creating disparities between regions with differing resources and infrastructures.

Labour market dynamics are shifting, with a reduced demand for low-skilled jobs and a growing need for specialized skills. Although new opportunities are emerging, particularly in higher-paid roles, these are often inaccessible to local communities in developing countries. The impact on current employment also varies, with some companies retraining employees, while others face job reductions.

The report also examines the extent to which technology adoption in emerging economies brings local benefits, where reliance on imported technologies might hamper broader economic growth. To address these challenges, the report offers policy recommendations aimed at ensuring that the benefits of technological change are shared more equitably across the sector.

1.2 Background and Purpose of the Study

The large-scale mining (LSM) sector is undergoing significant structural changes driven by the increasing demand for critical minerals arising from the energy and digital transitions, alongside growing pressure from investors, consumers, and civil society for more responsible and equitable mining practices (IGF, 2021, 2023). In response to these challenges, technological advancements offer valuable tools for mining companies to improve the efficiency of the sector both in terms of productivity and sustainability, though they also introduce a new set of challenges to navigate, for countries, communities, and mining companies themselves.

New technologies are rapidly transforming the LSM sector, with significant implications for labour markets, supply chains, and host communities. In 2021, with the support of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the IGF completed a 2-year research project called New Tech New Deal. This research mapped the key disruptive technologies that were expected to be adopted by the mining sector and assessed their potential impacts, particularly in mining-dependent countries (Ramdoo, 2019). The research was based on expectations and prospective scenarios that policy-makers could consider, given the likely socio-economic implications of disruptive technologies.

Since this report came out, the scale of technological adoption has broadened, and the pace of deployment across operations has accelerated. This new report provides examples of the actual impacts of some technologies on selected mining countries. It compares actual implications against the assumptions and expectations that were made in the previous report.

The results of this report draw lessons for governments, industries, and communities to better manage risks and opportunities related to the ongoing transformation in the LSM industry.

1.3 Countries and Operations Selection

This report is based on data collected from a sample of six LSM operations in six countries: Burkina Faso, Côte d'Ivoire, Guinea, Australia, DRC, and South Africa. In line with the previous research, the case studies have been selected from a set of criteria that consider different levels of countries' development as well as the maturity of the mining industry in those countries, different types of commodities mined, and different methods of production (such as underground or open-pit operations). Countries were chosen from various geographical locations. One of the key selection criteria for companies was the willingness of mining companies to share data, such as the impact of technologies on jobs.

As this report intends to assess the pace of adoption of new technologies considering countries' economic development, countries have been divided into two main categories:

- **Advanced mining economies** refer to middle- and high-income countries that have an established mining sector with a significant presence of large mining companies. Of the six countries selected, two countries—Australia and South Africa—fall into this category.
- **Emerging mining economies** refer to least developed and lower-middle-income countries that are nonetheless important and growing mining jurisdictions that have received a significant volume of investment in their mining sectors in the last few years. Of the six countries selected for this project, four countries—Burkina Faso, Côte d'Ivoire, Guinea, and the DRC—fall in this category.

A scoping desk study has been conducted to identify the individual operations that would be assessed. Criteria for such identification include the following:

- global criteria:
    - **different commodities**: The mining of different commodities requires different equipment, processes, and systems. This will help to review the impact of different existing technologies.
    - **various countries, jurisdictions, languages, and cultures**: Jurisdictional distinctions (technological regulation, taxation, security context, access to energy, network, development stage, etc.) have a strong impact on operations. This will help to show the impact of new technologies among different jurisdictions.
    - **various mining exploitation methods (open pit and underground)**: Different mining exploitation methods use different mining equipment and systems. This will help review existing technologies among different mining exploitation and their impact.
    - **operations owned by different mining companies**: Mining companies have different visions, strategic goals, and operating philosophies. This will help in reviewing existing technologies among different mining companies.
- key specific criteria:
    - **large workforce**: This will allow a focus on operations that have a higher social risk due to the large number of staff they employ in the country.
    - **engagement in a digital transformation**: This will help to focus on operations and key stakeholders with an acceptable digital maturity in order to get relevant information related to the impact of technologies.
    - **ability to access relevant and accurate data**: Considering the social responsibility and commitments of mining companies, access to information that could be considered sensitive, like considerations of potential job losses or reduction of local sourcing, is key to successfully achieving this study.
    - **operation in a mining-dependent country (for emerging countries)**: Technology may have more impact on mining-dependent countries due to the mining sector's strong contribution to national budget, employment, and socio-economic developments.

1.4 Scope and Limitations of the Report

This report focuses exclusively on the impacts of the development of new technologies in the LSM sector and does not address the artisanal and small-scale mining sector, which is the subject of a separate study (IGF, 2024a).

The report represents case studies from six LSM operations in six different countries, managed by six different mining companies. It intends to gather insights from some operations in specific circumstances and is not a quantitative study based on statistical samples. Indeed, although the countries were selected to ensure global representation, the sample size is insufficient to draw broad conclusions about the impact of new technologies on the mining workforce globally.

Additionally, limited data availability in some regions prevents the generalization of findings across countries with similar levels of development. Consequently, the data analysis presented should not be interpreted as a basis for generalizations applicable to all mineral-producing countries.

Instead, the report identifies key trends and, where appropriate, highlights specific examples to underscore important nuances and variations in the mining sector.

This report should also be read from the perspective that one of the main challenges encountered during the research was the reluctance of some mining companies to share data related to actual or expected job losses/workforce reductions. Such disclosure is indeed considered highly sensitive and a potential source of major social tensions among the workforce and in the vicinity of mining operations.

2.0 Overview of Technological Landscape

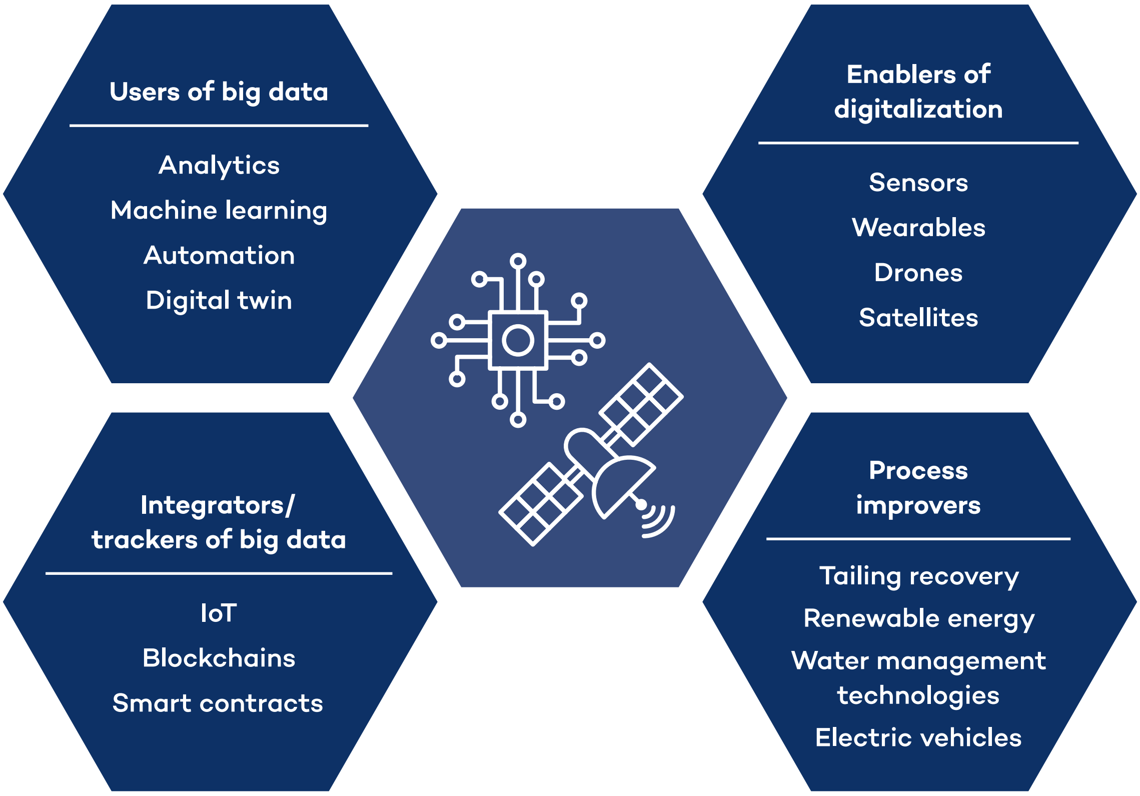
The technologies referred to in this report are a set of different types of technologies that are being adopted across various sectors, and not all of them are specific to the mining industry. However, when combined with mining equipment, they improve the efficiency, safety, and overall impact of mining operations (IGF, 2021).

2.1 Taxonomy of Disruptive Technologies

In its Technology Impacts Review, the IGF (Ramdoo, 2019) mapped key emerging technology trends that are being developed and adopted in LSM operations. Such technologies can be classified into four broad categories as illustrated in Figure 1:

- first, users of big data, such as **smart original equipment manufacturers (OEMs) machines and devices** embedded with technologies that use big data meant to boost the efficiency of mine operations, such as automated machineries, digital twins, super computers for big data analytics, etc.
- second, integrators, such as **advanced software technologies** that collect, analyze, integrate, and track big data, which are then shared through networks and high-speed connectivity. Examples include the Internet of Things (IoT), the use of 5G, virtual reality, blockchain technologies, etc.
- third, **enablers of digitization**, which provide an interface between human intelligence and AI. Examples include drones, sensors, connected wearables, etc.
- finally, **process improvers**, which are aimed at boosting performance, improving footprints of operations, and responding to environmental and social requirements. Examples include electric vehicles, water management technologies, renewable energy sources etc.

FIGURE 1. Taxonomy of disruptive technologies in the mining sector



Source: Ramdoo, 2019.[1]

2.1.1 Users of Big Data: Development of smart OEM machines and devices

Using big data, certain technologies enable machines to comprehend, learn, and respond to information, adjusting their actions as conditions evolve (PwC, 2017). Smart OEM machines embedded with machine interface capabilities allow the machine to be controlled (stop, teleoperate, slow down, etc.) by a machine control system. These machines can also be connected and exchange data with other smart devices (cameras, wearables, radar, etc.) through a communication network (radio, 4G network, wi-fi, etc.). They have some automation capabilities, such as changing some consumables, such as drill bits, without any human intervention.

They are often associated with enablers of digitalization such as smart devices (human-machine interface, tablets, wearables, cameras, sensors, drones, robots, etc.), which are also able to connect to a network, exchange data with each other and with machine control systems, etc. For instance, a camera installed in a truck can detect a human presence and send the information to the machine control system, which can decide to slow down or stop the machine.

1 See Ramdoo (2019) for a detailed breakdown of disruptive technologies and their uses in the mining sector.

2.1.2 Integrators - Advanced software (with high computing capabilities)

These advanced software technologies can collect and process large and complex amounts of data received from different sources (trucks, cameras, sensors, tablets, radar, other software, etc.). These types of software can use AI capabilities, such as machine learning, to predict and/or recommend set points (explosive quantity for a blast), help better visualize operations with augmented reality, etc.

2.1.3 Enablers of Digitalization

These include technologies, such as network communication technologies and cloud computing, that support the first two types of technologies. They allow large amounts of data to be exchanged among all the equipment, software, and devices in real time through high-speed connectivity, allowing information to be shared and processed instantly. Examples include 5G architecture, wi-fi, 4G, cloud computing, etc.

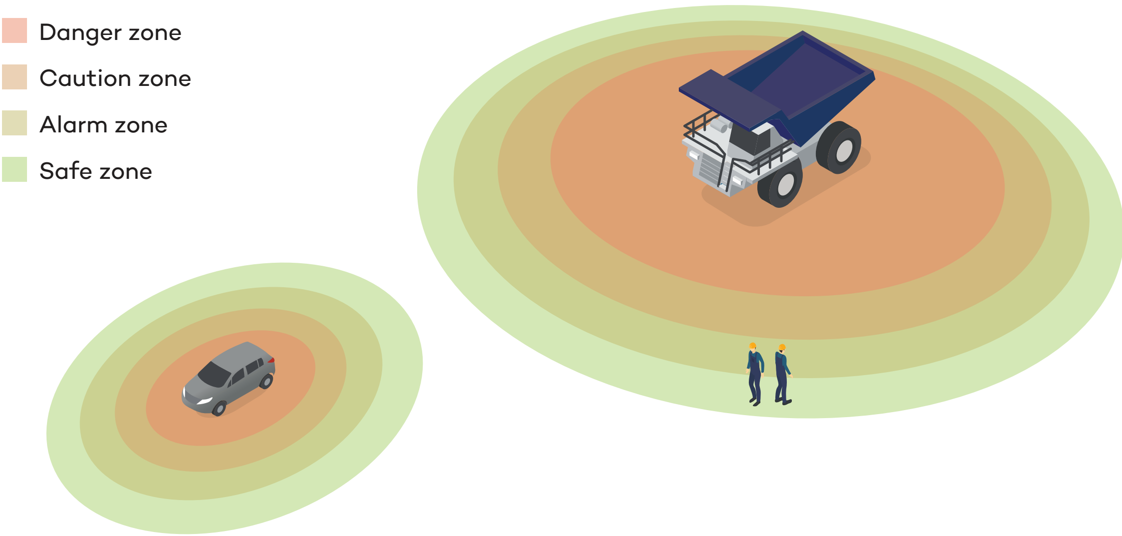
Combining these technologies enables their use in such cases as collision avoidance systems, as presented in Box 1.

BOX 1. MACHINE INTERFACE CONTROL: IMPROVING COLLISION AVOIDANCE AT MINE SITE

Intelligent vehicle control technology enhances safety on job sites by providing automation, remote control, and collision avoidance solutions for any mobile equipment (RCT Global, 2022). Advanced collision avoidance systems, illustrated in Figure 2, have the following components:

- collision avoidance system (CAS) monitors the external environment with the use of the Global Positioning System (GPS) and other sensors (cameras, radar, etc.) to detect objects and evaluate collision risk.
- machine interface control (MIC) monitors the operator's controls and intentions and passes this information to the CAS, which compares it with the external environment.
- the CAS uses this information to provide warnings to the MIC, which are then passed on to an operator or an automatic machine function (e.g., "slow down" or "stop") to execute interventional collision avoidance actions.

FIGURE 2. Illustration of CAS



Source: RCT Global, 2022.

Machine control systems also enable tele-remote guidance control and automation (drive by wire).

2.1.4 Process Improvers

Significant investments have been made in technologies aimed at improving mining processes to address environmental challenges and improve the sustainability of operations. These technologies cut across various opportunities. Examples include (a) the development of new mineral ore-processing technologies; (b) improved waste and tailings management techniques to improve mineral recovery; (c) water- and energy-saving technologies; and (d) the adoption of low-carbon e-mobility, such as electric vehicles. These are particularly important to mitigate the impact of mining on the environment (such as greenhouse gas [GHG] emissions) and to foster energy transition away from fossil fuel-powered operations.

2.2 Assessment Framework

Technologies assessed in this report are presented in Table 1. They have been selected based on their stage of development, their expected impact on mining operations and jobs, and on the socio-economic landscape around mine sites. As a result, they represent good proxies for assessing global technological development in the mining sector. They illustrate the degree of technological integration and can serve as an indicator of a company's technological maturity. The adoption of these technologies provides a comprehensive view of how mining companies are integrating digital, automated, and advanced tools into their operations, offering insights into their overall technological maturity and readiness for future challenges.

TABLE 1. New technologies assessed in the study

Technology	Description
(i) Users of big data	
Autonomous fleet (haulage, dozer, etc.)	Autonomous fleets consist of self-driving vehicles like haul trucks and dozers that can operate without direct human intervention. Autonomous haulage systems are widely adopted in LSM operations, particularly in open-pit mines. These systems increase safety and efficiency, making them a key indicator of a company's automation level and commitment to operational efficiency.
Autonomous fleet (drill rigs)	Autonomous drill rigs are automated machines that perform drilling operations without direct human control. They enhance precision and safety in drilling operations, reduce labour costs, and increase operational efficiency.
Autonomous fixed asset	Autonomous fixed assets are non-mobile machinery or equipment that operate independently, such as conveyors, crushers, or smelters. They automate fixed operations like material processing, increasing efficiency and reducing the need for manual intervention.
Advanced process automation	Advanced process automation involves using technology to automate complex tasks and processes that traditionally required human intervention. It is implemented to increase operational efficiency by automating processes such as ore processing, equipment operation, and monitoring systems.
(ii) Integrators	
Fibre optic/private LTE, wi-fi, 4G	These are high-speed communication networks that support the transfer of large amounts of data across mining operations. They enable real-time communication and data transfer, supporting the deployment of IoT devices and remote operations. Their widespread adoption is a proxy for digital infrastructure readiness in mining operations.
5G	5G is the fifth-generation technology standard for broadband cellular networks, providing faster data transfer speeds, low latency, and the ability to connect more devices simultaneously. In mining, it enables real-time data transfer, enhances communication, and supports the deployment of IoT devices, autonomous vehicles, and remote operations. 5G is rapidly being adopted in the mining industry, especially in regions with advanced infrastructure. It is a good proxy for assessing the overall digital connectivity and readiness of a mining operation.

Technology	Description
Data warehousing, business intelligence	Data warehousing involves storing large amounts of data in a central repository, while business intelligence tools analyze and visualize this data to inform decision making. It supports the analysis of operational data to improve efficiency, reduce costs, and optimize production. This technology is a strong indicator of a company's digital maturity and data-driven decision-making processes.
Software using AI to recommend and/or make autonomous decisions	AI-driven software analyzes data and makes autonomous decisions to optimize operations and safety. It is used for predictive maintenance, process optimization, and decision making in real time.
(iii) Enablers of digitization	
Drone	Drones are unmanned aerial vehicles (UAVs) used for aerial surveys, inspections, and monitoring. When equipped with GPS navigation systems and sensors, they perform measurement, in-situ scanning, and assessment to provide aerial data for mapping, surveying, and monitoring mine sites, improving safety and efficiency.
GPS	GPS is a satellite-based navigation system used to determine precise location. It helps navigation, mapping, and tracking equipment and personnel within a mine site. In open-pit operations, GPS technology can be used on blast-hole drills and electric cable shovels to achieve more accurate visualizations of drill point locations and shovel tracks. This information enables operators to accurately guide the drill from one blast hole to the next, maintain the desired shovel grade, or position the face, all from a remote location.
Radio-frequency identification (RFID) and real-time location systems (RTLSs)	RFIDs and RTLSs are small devices resembling stickers that can be attached to or embedded in any object. They contain antennas capable of receiving and responding to radiofrequency signals from a transceiver. These technologies are used to track and manage assets and personnel. In mining, they enhance asset management, safety, and inventory control by tracking equipment and personnel in real time.
Tablets/smartphones	Tablets and smartphones are mobile devices used for communication, data collection, and remote operation. They enable real-time data access and remote control of mining operations.

Technology	Description
Connected wearables	Connected wearables are devices that allow an interface between machines and humans, like smart helmets or vests that monitor worker health, location, and safety in real time. They improve productivity and worker safety by tracking vital signs, location, and environmental conditions. Adoption of such technologies can be a proxy for assessing a company's commitment to worker safety and integration of IoT technologies.
Immersive devices (virtual reality [VR], augmented reality [AR], mixed reality [MR])	Immersive devices such as VR, AR, and MR technologies create interactive and immersive environments. In the mining sector, they are used for training, remote operation, and visualization of mine planning and design.
(iv) Process improvers/other technologies	
Robot, humanoid	A humanoid robot has a body shape that resembles the human body. In mining, these robots can perform tasks that are dangerous for humans, such as inspection, maintenance, and even complex operations in hazardous environments. Humanoid robots are still an emerging technology in many industries, including mining. They are not yet widely adopted due to their high cost, complexity, and the fact that other forms of automation (e.g., autonomous vehicles) are more practical.
Additive manufacturing (3D printing)	Additive manufacturing, or 3D printing, is the process of creating a physical object from a digital model by laying down successive layers of material. In mining, it is used to create spare parts, custom tools, and components on site, reducing the need for inventory and downtime. Adoption of this technology can indicate a company's focus on innovative maintenance solutions and supply chain resilience.

Source: Author, based on Ramdoo, 2019.

3.0 Impact of New Technologies on Jobs

Each new technology listed in the framework (except humanoid robots) has been adopted in at least one of the six mining operations that were consulted for the case studies. For several reasons (access to connectivity, investment capabilities, the luxury to test unproven technologies, regulation, maturity of mining companies, etc.), developed mining economies (75% of adoption rate) are adopting more technologies than emerging ones (45%). This is Finding 2, presented in the Key Findings section.

The development of cost-effective connectivity systems should accelerate the adoption of technologies in the coming years.

Mining is becoming safer, more productive, and more responsible with the adoption of new technologies. However, there are important implications for the labour market and for suppliers, particularly in local communities. Women tend to be more impacted by the loss of opportunities (IGF, 2023). Indeed, very sophisticated technologies will require highly specialized skills, many of which are in new fields that don't exist yet in many countries, particularly in developing countries. The challenge for women, who already face a scientific skills deficit, is likely to be more significant.

The structural dynamics of the labour market are changing—new types of skills are being required, certain skills are evolving, and the demand for others is fading. The changes also create new job opportunities while restructuring some jobs and making others redundant with declining demand for some tasks.

This report does not provide a general assessment of the net impact on employment and value. It does, however, highlight the following trends observed at the mines consulted:

- New value pools are being created with the emergence of new business opportunities (such as tag manufacturers, drones, advanced software using AI, etc.). However, emerging mining economies are capturing few of these opportunities.
- Direct jobs created are not significant. They are, however, better paid and require qualifications that are not widespread in the mining sector. They are mostly related to fields such as information technology, data management, and engineering fields, such as mechatronics. The skills required make it difficult for local communities to capture these jobs. However, at the national level, skilled workers are able to fulfill the current demand, but their numbers are often limited. Furthermore, the skills supply may soon

be insufficient in the face of growing and competing demand and in the absence of proactive training systems to upgrade current skill sets or to train the labour force in the requisite skills.

- There are indirect job opportunities, notably due to new digital businesses. To access these skilled jobs, which represented the largest share of jobs created by the uptake of technologies in the mining sector, countries need to be able to create more value locally, either through the creation of companies that can provide technologies and services, or through other mechanisms, such as local content.
- Case studies show that the participation of women is still low—they filled 24.4% of the open positions related to new technologies, with wide disparities across types of occupations, such as drone operators (80%), data scientists (10%), and data analysts (10%). Addressing this imbalance requires specific policy instruments and actions by companies.
- Some technologies have had more drastic effects than others. For example, with the introduction of automated technologies aimed at improving safety (tele-remote) and productivity, the number of workers in mines has gradually fallen, especially for low- to medium-skilled occupations. The largest reduction in the workforce is happening in labour-intensive activities, especially on production lines, and around activities such as drilling, loading, and haulage. These account for the largest share of low- to medium-skilled jobs.
- However, the overall impact on jobs, especially the number of workers laid off, is less obvious at the moment, as the vast majority of mines have not yet adopted the most disruptive technologies, which are still somewhat experimental. In many countries, mining operations are striving to save as many jobs as possible to respect their initial engagements and avoid social conflicts that could affect the continuity of their operations.
- The main actions taken by mining companies to redirect workers to other occupations have included training and retraining of workers, with a particular focus on training programs for local communities.
- The main actions taken by governments have been to set guidance on the usage of certain technologies and enforce local content policies.

4.0 Key Findings

Over the past decade, most mining companies have deployed a range of new technologies in all aspects of their operations. With the growing pace of adoption, including of increasingly disruptive and autonomous technologies, there are likely to be multiple social, economic, and gendered impacts on the workforce, on local communities, and on supply chains, among others.

This paper is based on desk research and case studies grounded in interviews conducted with six LSM companies operating across six countries at different levels of development. Companies selected operate both underground and open-pit mines and mine different commodities. For confidentiality reasons, the names of companies are not mentioned. The report outlines eight key findings, which cover the current technologies being deployed by companies surveyed and their impacts, and measures taken by mining companies and governments to address these challenges and leverage opportunities.

FINDING 1

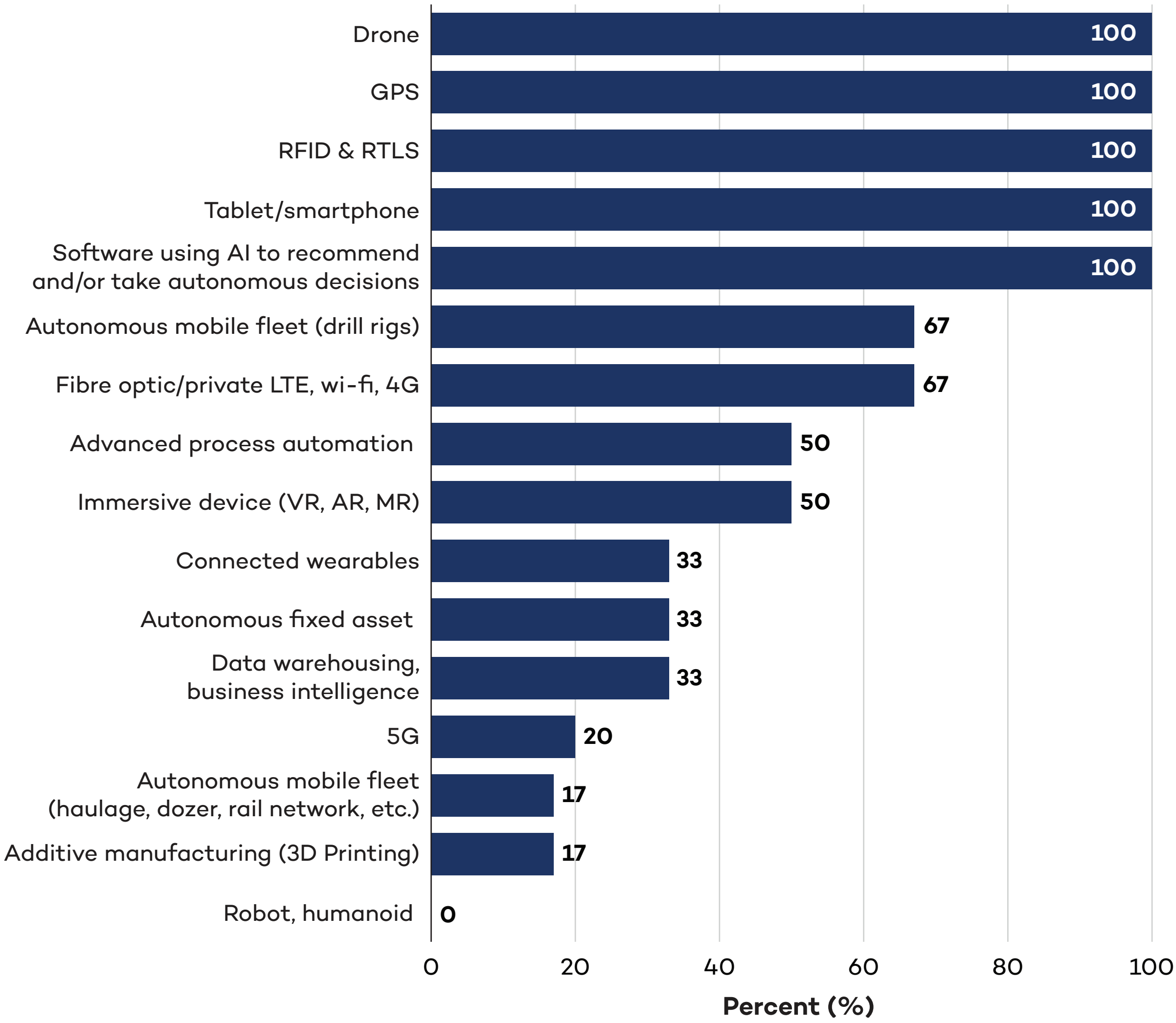
The future is already here: Almost all "new" technologies have already been adopted by mining companies.

A wide range of disruptive technologies once considered "new" have now already been widely adopted in LSM operations, both in metalliferous and bulk commodities.

Figure 3 highlights that, except for humanoid robots (i.e., robots resembling the human body in shape), several new technologies have already been implemented in at least one of the mining operations surveyed for this report.

The case studies also revealed that the average adoption rate of new technologies in underground operations is higher than in surface mining. This is largely explained by two main aspects. First, underground mines are more complex to operate, and therefore, investments in technologies are aimed at improving efficiency and productivity. Secondly, workers in underground mines face inherently higher safety risks and, therefore, investments in technologies are aimed at improving the work environment to minimize occupational and safety risks for workers.

FIGURE 3. Adoption rate of new technologies by mining companies based on the survey



Source: Author, based on data gathered for this study.

The results of the survey align with the findings of a study conducted in Canada (Mining Industry Human Resources Council, 2019), which ranked the top five reasons for mining companies to invest in new technologies thusly:

- improvement in health and safety of miners in the workplace
- cost reductions to increase competitiveness
- improvement of efficiency, performance, and productivity of operations
- improved environmental sustainability
- the recruitment of new and/or higher-skilled workers.

When making a choice on tech-related projects, mining companies consider several factors, such as the economic and geopolitical context of the operation, the availability and quality of infrastructure (transport, water, energy, and connectivity), the ore body configuration, the ore quality and accessibility, security concerns, the relations with communities, the level of education and technical expertise, the availability of skilled workers, etc.

However, there are several unknowns, such as geological uncertainties and price volatility, that may impact the economics of the project and investment decisions. In that regard, some technologies may provide a way for the industry to gain greater control over certain aspects of the mining project. For example, the use of AI can help to improve the accuracy of the ore grade predictions. This can help companies make better decisions about where to mine and how to allocate resources throughout the life cycle of projects.

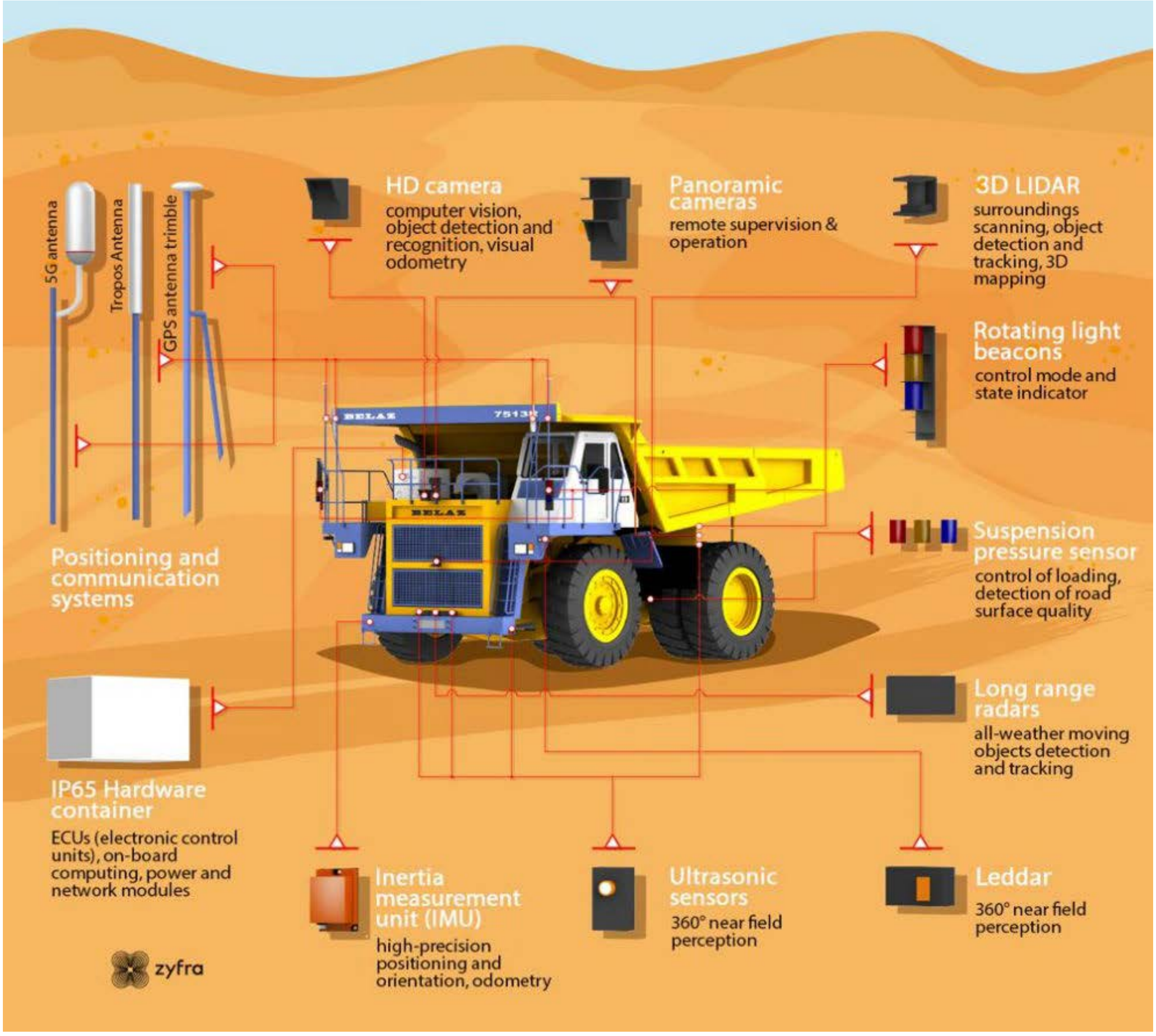
Although the pace of adoption has increased noticeably in recent years, it is important to highlight that technological adoption is not new in the mining industry. Individually, some technologies have been implemented for more than 15 years. These include drone-based surveys, RTLSs, and sensors, for example. Drones have been used for pit mapping, stockpile measurement, highwall mapping, inspections, and security, while RTLSs have been used to track assets, such as vehicles and trucks, and automate the counting of truck trips. Sensors have been used to capture noise, temperature, or air quality in the processing system. These are now deeply embedded in fleet management systems.

What is different and perhaps new, however, is that the recent evolution of technologies has allowed the combination of multiple technologies to operate simultaneously, which multiplies the capabilities of technologies for higher performance.

For instance, an autonomous truck is a typical example of the combined use of different technologies used for various purposes, illustrated in Figure 4 (Tanase, 2020). Some of the technologies embedded in a mining autonomous truck are

- GPS: This technology provides the truck's location and allows it to follow a predetermined route.
- light detection and ranging (LiDAR): LiDAR uses lasers to create a 3D map of the truck's surroundings. This allows the truck to avoid obstacles and navigate safely.
- sensors: A variety of sensors are used to detect objects and people in the truck's path. This includes radar, cameras, and ultrasonic sensors.
- artificial intelligence: Machine learning is used to train the truck's software to make better decisions about its path. Computer vision is a branch of AI used to capture and analyze data from sensors, such as cameras.
- communication systems: The trucks communicate with each other and with a central control system to receive instructions and send status updates.
- software: The truck's software is responsible for controlling the truck's movements and making decisions about its path.

FIGURE 4. Illustration of new technologies embedded in a mining autonomous truck



Source: Tanase, 2020 (with permission).

Deployment of fleets of autonomous vehicles at mine sites has been ongoing for more than 15 years and is now widely spread in mining operations around the globe (see Box 2).

BOX 2. HIGHLIGHT

The mining equipment manufacturer Komatsu initiated trials of its autonomous haulage system at Codelco's copper mine in 2005, in Chile. By 2008, the system was officially introduced for commercial use. That same year, autonomous trucks were deployed in Australia at Rio Tinto's iron ore mine.

In 2018, more than 130 of Komatsu's autonomous trucks were in operation in mining sites in Chile for copper, in Australia for iron ore, and in Canada for bituminous sands (Equipment Journal, 2018).

FINDING 2

The adoption of new technologies in the mining industry is more prevalent in advanced mining economies than in emerging mining economies.

Figure 5 shows that, for the six case studies, the adoption rate of new technologies is higher in advanced mining economies. The average adoption rate in selected mines in emerging mining economies was 45%, compared to 75% in mines operating in advanced mining economies.

The top adopted technologies were drones (UAVs), sensors, tablets/smartphones, AI software, and GPS. Regarding autonomous equipment, autonomous drilling rigs were more prevalent than trucks in emerging mining economies, while the operations located in advanced mining economies examined had already adopted autonomous truck fleets.

The main reasons why mining companies in advanced mining economies are more likely to adopt new technologies include financial capabilities, higher labour costs and skills availability, high-speed and reliable IT networks and connectivity, and an enabling regulatory environment that allows the adoption—and ensures the protection of—data and information systems.

Advanced mining economies, including Brazil, Russia, India, China, and South Africa, have larger operations operated by better-capitalized mining companies compared to emerging mining economies. Because larger mining companies have more **financial resources** to invest in new technologies, they can also afford to take on higher associated risks. For example, the cost of automating an existing dump truck in Australia is around USD 1 to USD 1.2 million, which is the cost of a new truck in West Africa. However, the cost of these technologies is expected to decrease and will become more affordable over time, expanding their reach to a wider number of mining companies, including those operating in emerging mining countries.

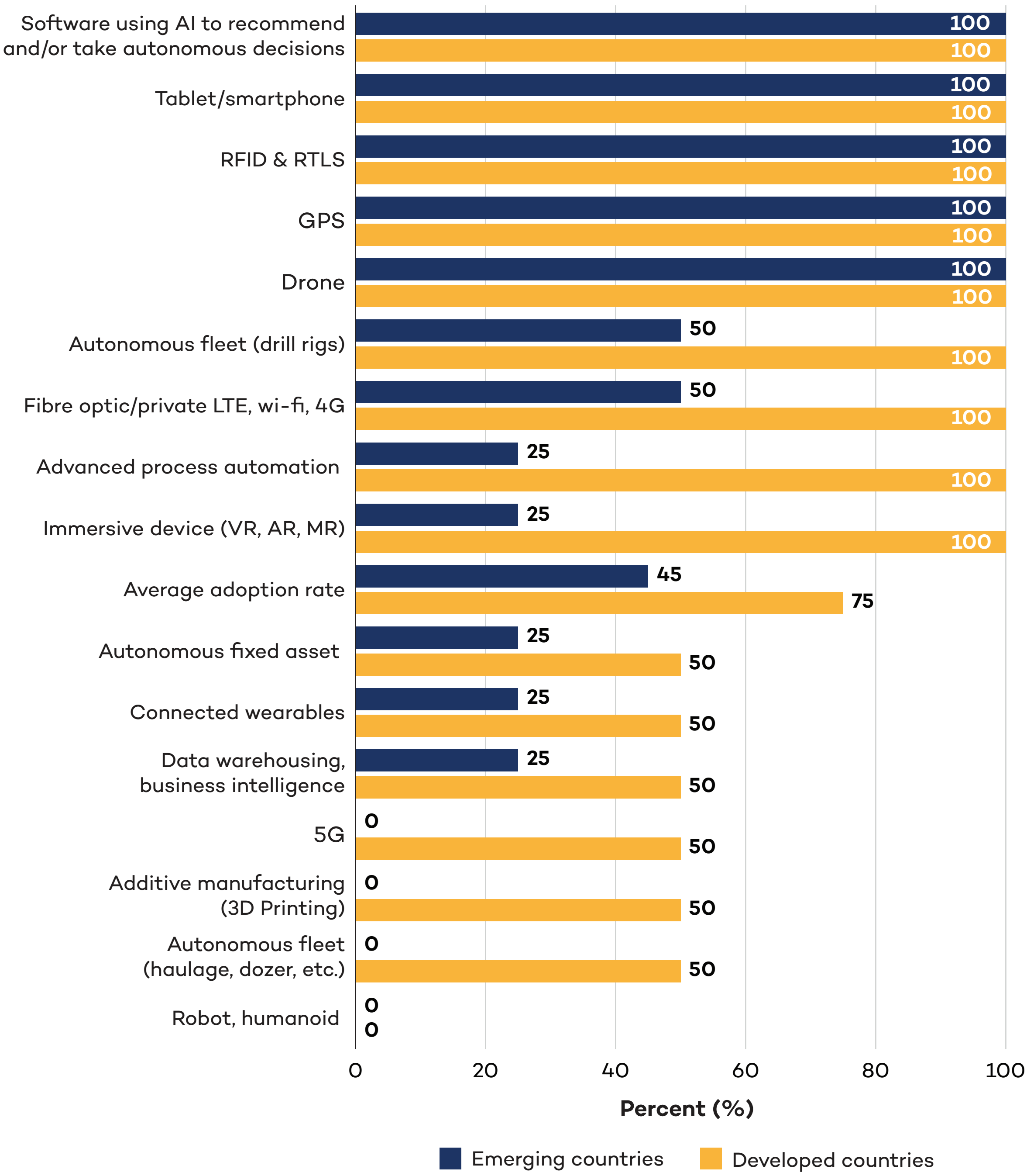
Furthermore, some advanced mining economies face labour shortages, notably for occupations such as truck drivers (International Road Transport Union, 2022).[2] In addition, **labour costs** are higher in advanced mining economies than in emerging mining economies. The use of autonomous haul trucks offers the most significant opportunity for cost savings in mines with a high number of haul trucks and in countries with high labour costs (Parreira, 2013).

However, the cost of labour is not sufficient by itself to pay back investment in automation. Other key factors, such as safety, productivity, reduction of fuel consumption, tire wear, employment policies, and the culture of innovation, play a key role.

Reliable and high-speed connectivity is a major barrier to the adoption of new mining technologies in emerging mining economies, as they often require real-time data exchange. A network with high-speed connectivity and low latency is crucial to ensure quick transmission of commands and feedback between the automated devices and control systems. For example, autonomous mining vehicles need to be able to communicate with each other and with a central control system to operate safely and efficiently.

[2] The International Road Transport Union's (2022) Global Driver Shortage Report survey, which targeted more than 1,500 commercial road transport operators in 25 countries, found that the industry faces a shortage of more than 2.6 million professional drivers globally.

FIGURE 5. Adoption by level of countries' economic development



Source: Author, based on data gathered for this study.

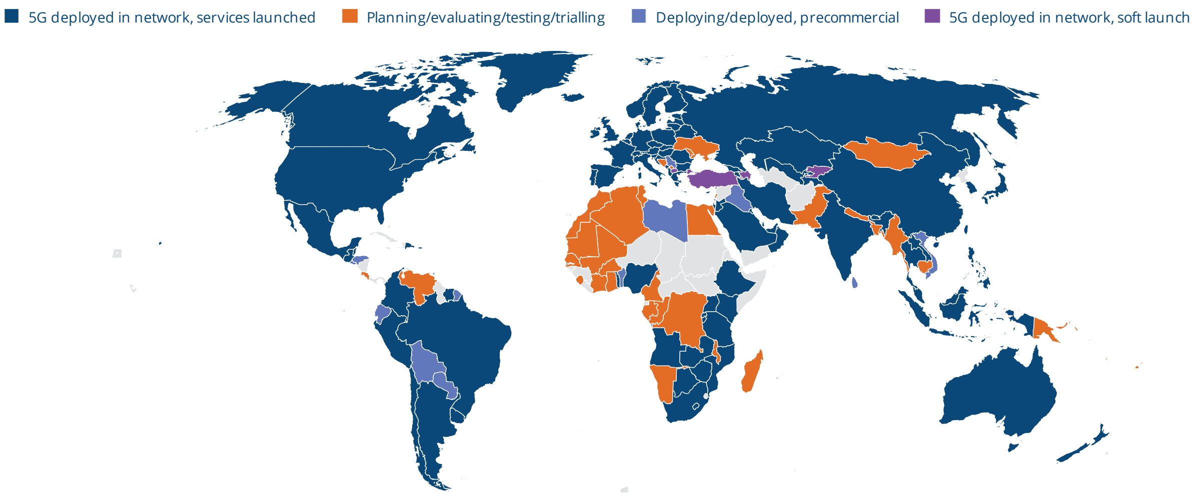
In addition, **the cost of network connectivity** is a barrier for mining companies in emerging mining economies. This is especially true for small and medium-sized mining companies, which may not have the financial resources to invest in high-speed internet access when these services are not already available in the mining region.

In a recent survey conducted in 2021 by AXORA (2021), 38% of the mining companies acknowledged the lack of IT infrastructures to handle data generated by digital solutions as a major bottleneck for investments in new technologies.

It is fair to say that in recent years, network connectivity has improved in emerging mining economies. A few mining companies, notably based in West Africa, are using 4G, private LTE, or wi-fi to deploy autonomous machinery. For example, IAMGOLD launched the first semi-automated drill rig in Burkina Faso, with assistance from Epiroc, in February 2020 using Cisco wi-fi (Gleeson, 2021).

Several tests for 5G deployment are also underway with mobile operators and technology providers in emerging countries, especially in Côte d'Ivoire with Orange (Orange Côte d'Ivoire, 2023). These developments are expected to boost the adoption of more digitalization and automation systems in the coming years. A map of available 5G networks globally is presented in Figure 6.

FIGURE 6. Map of 5G network as of March 2024



Source: Global Mobile Suppliers Association, 2024 (with permission).

BOX 3. HIGHLIGHT

In 2021, through a partnership between Shanxi Xiangning Coke Coal Group, China Unicom Industrial Internet, and Huawei, a 5G private network was deployed in the Yanjiahe coal mine in China (GSMA, n.d.). The network connects underground operations with the equipment room aboveground, where videos captured by high-definition cameras are used for content analysis and risk identification.

Access to digital infrastructure and the possession of digital skills are also essential elements for connectivity: these are highly critical for upskilling and reskilling workers in the mining industry, especially as automation and technological advancements transform the sector. The **Women and the Mine of the Future** project highlights that in higher-income countries like Australia, where 65.5% of the population is digitally proficient, women have better opportunities to transition into digitalized roles (IGF, 2023). However, in lower-income nations, where the digital gap is more pronounced and access to resources is limited, mining communities, particularly women and other underserved groups, face significant challenges in acquiring the skills needed for emerging roles. Closing this gap is critical for equitable participation and socio-economic benefit in the future of mining.

FINDING 3

New technologies have had a major impact on the dynamics of the labour market.

New technologies have had multi-level impacts on direct employment in the mining sector. Technologies embedded in various activities fundamentally changed the nature of tasks, which, therefore, required important changes in skills needed to perform these tasks (IGF, 2023).

As more technologies are adopted and/or embedded in mining operations, there are direct consequences for the workforce structure, which is changing accordingly. Notably, and unsurprisingly, the industry has observed a constant decrease in demand for low-skilled workers and, consequently, an increase in demand for more skilled workers from mining-specific jobs and for other cross-functional professionals (digital project manager, business analyst, data scientist, data analyst, etc.), which fetch a higher wage.

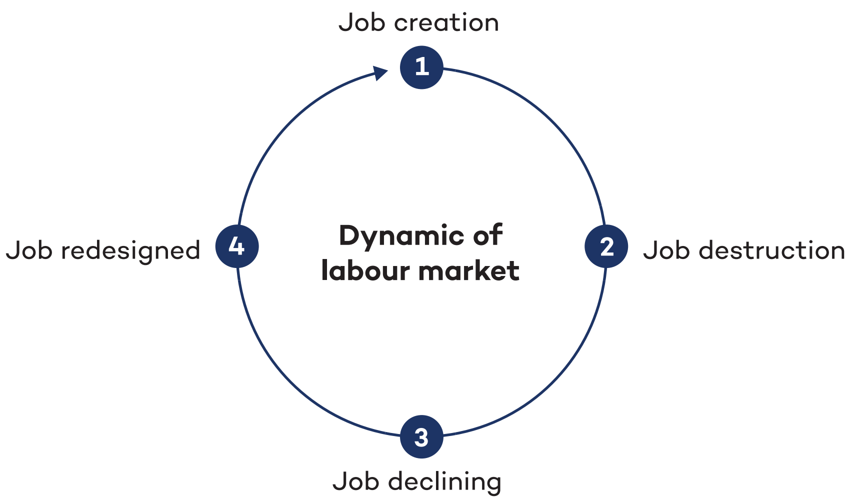
BOX 4. HIGHLIGHT

The **Women and the Mine of the Future** project highlights how these technological advancements intersect with existing gender disparities in mining communities, particularly skills deficits. Women in many countries, despite often having higher educational attainment, have limited access to technical skills. In countries like Ghana and Zambia, only 16% of women in the mining and quarrying sector possessed basic, intermediate, or advanced education in 2017, compared to 84% of men. Moreover, women made up just 10% of the skilled workforce in Ghana's large-scale mines by 2020, with most of them being non-Ghanaians (IGF, 2023).

These trends reflect broader inequalities, as technological uptake increases the risk of redundancy for low- to mid-skilled workers, including clerical support staff, drivers, and plant and machine operators. Notably, women are overrepresented in clerical support roles, a category highly vulnerable to technological displacement. Yet, there has been a positive shift, particularly in countries like Mongolia, where the share of women employed as machine operators grew from 6% in 2014 to 15% by 2020 (IGF, 2023). These developments raise questions about the impact of technological advancements on women's future roles in mining and highlight the necessity of targeted upskilling programs to ensure women can transition into more stable, technologically integrated positions.

Every new technology adopted by the LSM companies identified for this report had an impact on jobs. However, the degree of impact observed was different, with some technologies having more impact than others on the mining labour market structure. As presented in Figure 7, the impacts can be summarized in terms of (i) creation of new jobs, (ii) the elimination of some occupations made redundant due to automated functions of machinery, (iii) the gradual reduction in demand for certain occupations as more technologies are embedded into mining operations, and (iv) the reconfiguration or redesign of tasks as the operation of technologies require additional competencies in current occupations.

FIGURE 7. Simplified representation of labour market dynamics



Source: Author.

Table 2 summarizes the findings from the company case studies conducted for this report. The 1-to-4 stars impact score assigned to each technology reflects the diversity of job impacts observed by the companies interviewed. For example, a technology that has only had an impact on job reconfiguration would receive one star, while a technology that has had an impact on both job reconfiguration and job losses would receive two stars.

TABLE 2. Impact score of technologies in mining labour market

№	New technologies	Impact score
1	Drone	★★★★
2	Software using AI to recommend and/or take autonomous decision	★★★★
3	Autonomous fleet (drill rigs)	★★★★
4	Autonomous fleet (haulage, dozer, etc.)	★★★★
5	Autonomous fixed asset	★★★★
6	RFID & RTLS	★★★★
7	Software using AI to recommend and/or take autonomous decision	★★★★
8	Connected wearables	★★★
9	GPS	★★
10	RFID & RTLS	★★
11	Tablet/smartphone	★★

Nº	New technologies	Impact score
12	Data warehousing, business intelligence	★★
13	Advanced process automation	★★
14	Immersive device (VR, AR, MR)	★★
15	Additive manufacturing (3D printing)	★★
16	Cloud computing	★★

Source: Author, based on interviews and data collected for this study.

The table shows that all technologies had an impact on at least two features of occupations. In fact, close to 50% of the technologies surveyed impacted all aspects of the job market for those occupations. This is an important finding as it indicates that policy-makers need to have a comprehensive understanding of change to ensure workers can adapt to new jobs or can be retrained to other occupations, where possible.

New roles have emerged in the mining industry, offering new perspectives for mining-specific jobs and job opportunities for cross-functional professions.

Based on the mining projects examined for this report, Table 3 highlights 38 new roles that have emerged in mining companies involved at the operations and group levels. Furthermore, Appendix A lists the indirect occupations stemming from the development of new technologies.

LSM is a capital-intensive industry that requires technical and specialized skill sets. Therefore, opportunities to work in the mining industry are often considered difficult to obtain. Future mining jobs are likely to require more highly specialized skills.

Furthermore, with the advent of new technologies, new opportunities are opening up in fields not traditionally considered as key for the mining sector. Professionals who once had few opportunities to enter the sector are now becoming precious talent to attract. More importantly, they are being sought after by many other industries and sectors and, therefore, need to be retained. The case studies show that 73% of new roles created in relation to new technologies have been filled by people from non-mining backgrounds and industries, while the remaining ones have been filled by in-house employees who benefited from additional training.

TABLE 3. New jobs created due to new technologies

New technologies	New direct occupation created in mining companies*
Drone	• Drone operator • Drone operator assistant • Drone maintenance technician • Drone operations coordinator • Drone operations manager
Connected wearables	• Wearables data analyst
GPS	• GPS installer & maintainer
RFID & RTLS	• Asset-tracking specialist • Data analyst
Tablet/smartphone	• Mobile app developer
Software using AI to recommend and/or make autonomous decisions	• Data/big-data engineer • Data scientist • Data analyst • Dispatch engineer • Dispatch technician • Dispatch system engineer • Fleet management system specialist • Software developer • UX/UI designer
Data warehousing, business intelligence	• Data architect • Data/BI analyst • BI systems specialist • Data engineer
Advanced process automation	• Robotics process automation developer • Automation project manager
Autonomous mobile asset	• Autonomous systems engineer • Autonomous vehicle maintenance technician • Autonomous vehicle software engineer
Immersive device (VR, AR, MR)	• Training simulation room operator
Additive manufacturing (3D printing)	• 3D printing consultant
Cloud & 5G	• Network specialist • Network administrator • Cloud engineer

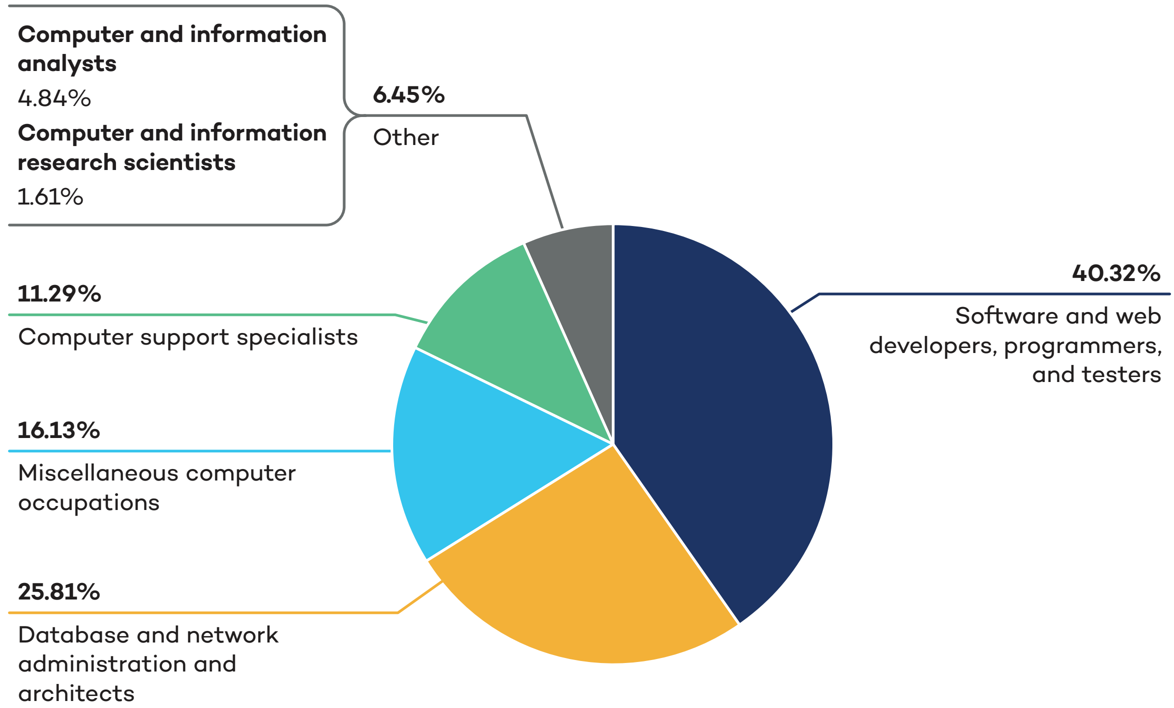
New technologies	New direct occupation created in mining companies*
Combined use of technologies	• Digital transformation manager • Digital project manager • Digital product manager • Data manager • Cybersecurity specialist • Business analyst

Source: Author, based on data gathered for this study.

Given the pervasive use of digital and IT-related technologies, the survey revealed that 70% of new direct occupations recruited in mining companies are IT and data-related jobs. These jobs were not mine-site related a few years ago. They require skills in advanced statistics and software programming, among others, which complement existing requirements in science, engineering, and mathematics.

An example from Australia shows that in 2022, around 40% of IT hiring in the mining industry (direct and indirect jobs combined) was in the software and web developers, programmers, and testers job classification (GlobalData, 2022).

FIGURE 8. Share of IT hiring in the mining industry in Australia in March 2022, by job classification



Source: GlobalData, 2022.

The pace of implementation of new technologies in mining companies depends on the corporate strategy. While the most common model of technological adoption is to acquire off-the-shelf-solutions, some companies choose to use a mixed approach, by setting up in-house digital teams to develop advanced software for their multiple operations. The Australian example illustrated in Figure 8 shows that in 2022, around 1.6% of IT hiring in the mining industry in the country was in the computer and information research scientist category. Although this number seems rather small, it nonetheless points to the fact that mining companies are slowly building in-house expertise to design their own solutions. By building in-house expertise, mining companies are more likely to create more direct job opportunities. Developing in-house technologies can also help companies better prepare their employment plans, based on the types of tasks and occupations that will be needed to operate home-grown technologies. Skills anticipation plans can be discussed with governments and training institutions accordingly.

BOX 5. HIGHLIGHT

Endeavour Mining, the leading gold producer in West Africa, launched its digital transformation program in 2021 (Endeavour Mining, 2022). The company has used a mixed approach, combining off-the-shelf solutions and in-house development. This has led the company to set up an internal innovation office team with the recruitment of new profiles, such as data scientist, data engineer, data analyst, software engineer, etc. These jobs are classified as high-skilled jobs and are paid 3 to 5 times more than low-skilled jobs.

Every activity in the value chain where technologies have been introduced has redesigned related occupations.

Almost all mining-specific jobs have been redesigned with the adoption of new technologies, which has resulted in significant changes in occupational structures and in specific tasks that are performed by workers. Three main types of changes are observed:

- **task suppression**: Some tasks that were previously executed by workers are now being fully performed by new technologies. This has resulted in the elimination of some specific tasks, often replaced by others to monitor the technologies instead. One example is the use of driver assistance functions in dump trucks, which has led to the suppression of tasks such as speed monitoring or braking control performed prior to this function by the drivers. Now, drivers are responsible for overseeing the correct operation of these automated functions.
- **changes in the nature of tasks**: New technologies have redesigned the nature of some tasks. These new technologies help improve the efficiency of the tasks and the productivity of workers. For example, the use of computer-aided design software has changed the way that mine plans are created. When done by machines, there are fewer errors, and workers can focus their attention on improving the quality of the plans for better execution.

- **new tasks**: As mentioned already, some new tasks have been created thanks to new technologies. For example, the use of drones has created new tasks for mine operators, such as defining and setting up the flying plan for surveying and inspecting mine sites. Drones are meant to augment the capabilities of workers, making them more efficient in their jobs, and collect a vast amount of real-time data, which is generally processed with powerful software. New tasks have emerged to process, analyze, and interpret the data to improve the viability of mining projects.

BOX 6. BREAKING DOWN ROLES: TASKS VS. OCCUPATIONS

A **task** refers to a specific, often smaller unit of work with a clear goal, such as monitoring equipment performance, entering data, or operating machinery. Tasks are actions that, together with other tasks, form a complete role.

An **occupation**, on the other hand, is a broader role encompassing a set of related tasks and responsibilities. For example, "mining equipment operator" is an occupation that includes multiple tasks, such as operating heavy machinery, monitoring safety protocols, and conducting routine maintenance.

Considering that an occupation is a set of tasks, when tasks change, it does not necessarily mean that the occupation becomes redundant. The workers need to be retrained and reskilled. For instance, if a truck operator is asked to carry out tele-remote operations (operating the truck outside the cabin), they will keep their job and be trained on tele-remote operation.

Interviews with mining companies selected for the case study revealed a set of skills that have been relevant to operating in this new context.

- active learning and adaptation
- critical thinking and problem solving
- reading and writing
- remote operation
- remote operation control
- data entry via software
- basic technological troubleshooting
- cross-data analysis
- business process elaboration and improvement
- usage of AI recommender & understanding bias
- basic cyber risk identification & mitigation

The demand for some jobs has decreased, and some have been eliminated, especially in mine production, which employs a large number of workers.

Technologies such as automation are performing major tasks within some occupations. Automation is the use of machines to perform tasks once done by humans. This has led to a reduction in the demand for human workers in the mining industry.

Table 4 shows examples of declining occupations and occupations made redundant by technology across the new technologies adopted by the mining companies surveyed. The top five technologies that have had significant impacts are

1. autonomous mobile assets (trucks, drill rigs, excavators, etc.)
2. software using AI to recommend and/or make autonomous decisions (fleet management system, digital twins, etc.)
3. drones
4. RFID & RTLS
5. tablets/smartphones

It's important to note that it is the combination of multiple technologies that has enabled the capability to fully or partially automate entire processes previously executed by different categories of workers. Also, new mines designed using new technologies at the beginning of their operations do not hire for certain positions (ore spotter, helper) and hire fewer workers for certain jobs that will be redesigned (e.g., three manual truck operators who could be replaced by one tele-remote operator, some field pits supervisor that could be replaced by a control room supervisor, etc.).

TABLE 4. Destroyed and declining jobs due to new technologies

New technologies	Jobs destroyed	Declining jobs
Drones	None	• Surveyor assistant
RFID & RTLS	• Tallyman	
Tablet/smartphone	• Data entry clerk	
Software using AI to recommend and/or make autonomous decisions (fleet management systems, digital twins, etc.)	• Offsider • Data entry clerk • Tallyman	• Ore spotter • Pit supervisor • Pit controller • Foreperson • Underground production miners
Autonomous mobile assets (trucks, drill rigs, excavators, etc.)	• Ore spotter • Drill offsider • Data entry clerk • Tallyman	• Pit supervisor • Pit controller • Foreman • Underground production miners • Dump truck operator • Drill rig operator • Excavator operator • Loader operator • Machine operator

New technologies	Jobs destroyed	Declining jobs
Data warehousing, business intelligence	• Data entry clerk	

Source: Author, based on data gathered for this study.

All the above-mentioned occupations are in the mine production-related activities.

In West Africa, at the asset level, the study showed that production occupations in a bauxite mine company in Guinea represent about 55%–66% of the total head count for a mining operation. This ratio goes up to 75%–85% on the mine production contractor side.

At Chirano Gold Mines in Ghana, which employed 1,112 people in 2020, the surface and underground mining workforce represents 55% of the total headcount. Assuming supervisory staff represent 5%–10%, the production teams represent 45%–50% of the total workforce (IGF, 2022).

In Canada, production occupations represent 32.2% of the mining workforce, with an average vulnerability score of 0.7/1 according to the Mining Industry Human Resources Council of Canada's (MiHR's) Occupational Vulnerability Index, a composite score to gauge the vulnerability of 120 mining-relevant occupations developed by the MiHR in 2019. This composite score quantifies the mining workforce's exposure to disruption, taking into consideration the likelihood of displacement due to technology, as well as workers' ability to find equal or better employment. As a result, current jobs in production might witness increased competition between workers to keep or obtain them. On the other hand, workers in production at the mine site could become the privileged pool to draw from for the mining industry while training individuals for new occupations because they already have the mining mindset and expertise that newcomers may lack.

FINDING 4

Net impact on direct jobs depends on the adoption level of new technologies.

Not all uses of technology in the mining sector are job destroying, particularly technologies that digitize processes using software. Regarding automation, as the level of automation increases (from one operator/one machine to one operator/several machines), mining companies have seen their workforce gradually decline and redeployed into other functions (whenever possible) when training was provided. In fact, Table 5 describes the impact of the adoption of new technologies on jobs in a sample of five mining companies at different levels of technology adoption.

TABLE 5. Net impact on jobs from new technologies, example from case studies

Type of technologies	Non-autonomous (digitalization of processes, CAS, line-of-sight operation, etc.)	Tele-remote operation	Autonomous
Companies	Company A & B	Company C & D	Company E
Description	Introduction of sensors in the mobile fleet (trucks, excavators, drill rigs, etc.) and software to augment the driver's productivity (speed control, fuel consumption, etc.). Production data are automatically collected and transmitted.	Introduction of mobile fleet that can be operated remotely (outside the cabin). Operator remotely controls the machine with the help of multiple cameras and sensors. One piece of equipment is tele-operated by one operator.	Adoption of autonomous machines. One operator operates multiple (three) trucks simultaneously.
Direct job creation	19	14	20
Direct job losses	2	29	36
Net direct impact	+17	-15	-16
Comments	**Job destroyed** • Offsider • Data entry clerk **Job created** • Data scientist • Data analyst • Software engineer • Dispatch engineer • Digital project manager	**Job destroyed** • Offsider • Data entry clerk • Tallyman **Job created** • Automation engineer • Network specialist • Data analyst • Software engineer • Maintenance specialist	**Job destroyed** • Operator • Offsider • Data entry clerk • Tallyman **Job created** • Automation engineer • Network specialist • Data analyst • Software engineer • Maintenance specialist

Source: Author, based on case studies in this report.

Numbers in this table should not be considered as general because they stem from specific case studies of what happened in these operations. It is not an assessment of the global impact on the workforce expected from automation. Depending on the company context (growth, local content policies, relation with unions, etc.), the workforce can be kept in the operation even if redundant to avoid job losses, deployed in other departments, transferred to another operation that is under construction, etc. What is sure is that a new mine operation that operates autonomous equipment will surely hire a smaller workforce to operate its fleet.

Local communities are highly impacted as mining operations become autonomous. Technological evolution has the ability to increasingly automate the predictive, repetitive, and manual tasks generally performed by low-to mid-skilled workers. Usually, workers from local communities perform unskilled and low-skilled jobs, such as bush clearing, housekeeping, machine operating, drilling helpers, security, etc. Research conducted for this report found that 35% of job losses in surveyed mining companies were occupied by local community members. Indeed, most occupations held by local communities' workers, and in some cases mostly by women (machine operators, data entry clerks, offsiders, etc.), are entry level (unskilled or low-skilled) and subject to automation.

The applications of mine automation technologies have resulted in an increase in demand for more skilled workers to operate the systems and, at the same time, a reduction in the number of employees based at the mine site due to the creation of remote operation centres where operations are now controlled and monitored. While technologies have decreased overall skills requirements for the labour force locally, it has resulted in reduced employment opportunities in the local communities.

A great example is the Gudai-Darri autonomous mine in the remote Pilbara region in Western Australia, which is operated remotely. One (rather poetic) description of the mine's operations is provided in Box 7.

BOX 7. DESCRIPTION OF A REMOTELY OPERATED MINE IN AUSTRALIA

Operating an LSM operation remotely, even from a long distance, is already happening, as illustrated in the description below from the Gudai-Darri mine operated by Rio Tinto in Australia (Rio Tinto, 2022).

> As a large-haul truck pulls up for the day, you might expect to see a weary driver climb out of the cab. But at Gudai-Darri, our fleet doesn't retire for the day. They're running 24/7, without a single driver in sight. And that's because the entire truck fleet is being directed by a controller sitting almost 1,500 kilometres away, overseeing trucks on site from the relative safety and comfort of a control room in Perth.
>
> Seated next to them, another controller might be remotely operating one of the autonomous drills somewhere else on the site, or our autonomous AutoHaul™ rail network, or one of the world's first autonomous water carts—advanced mining through a successful collaboration with the leading equipment manufacturer, Caterpillar, and that use onboard AI to monitor dust levels and automatically spray water when conditions require it.

Source: RioTinto, 2022.

FINDING 5

More opportunities have been created for women, but more must be done to help them take full advantage.

Among new occupations created by the deployment of new technologies in the mining companies surveyed in this study, women have filled 24.4% of the open positions, distributed across drone operators (80%), data scientists (10%), and data analysts (10%).

The reconfiguration of digital mining operations has led to the relocation of part of the workforce toward remote centres now based in cities and has improved working conditions and safety of workers through the tele-operation of heavy equipment. While these have created new roles, the working environment is arguably more conducive for women, contributing to addressing some of the systemic challenges they previously faced, such as the safety of some jobs, driving heavy mobile equipment during pregnancy, living in male-dominated areas with the high risk of harassment, physical separation from their families, the harshness of some field tasks, etc. But in reality, uptake of these jobs by female employees has not lived up to expectations (IGF, 2023).

Since 2008, Codelco's Gabriela Mistral (Gaby) open-pit mine located in Antofagasta in Northern Chile has used Komatsu autonomous trucks exclusively (Moore, 2024). It was the first mine in the world to do so. It currently has 25% of women employees, compared to 16% for the whole company (Committee for Economic Development of Australia, 2023). Furthermore, a woman has been general manager of this mining division since 2023 (Mining.com, 2023).

One of the reasons for the slower uptake of new digital jobs by female workers is that most of the new occupations created by digital technologies are in STEM-related fields. While more demand for expertise in those fields could open opportunities to increase the presence of women in those occupations, women are still lagging when it comes to digital skills (IGF, 2023).

To provide more opportunities for women, deliberate measures should be taken to overcome the challenges they face in gaining access to digital jobs within mining companies.

BOX 8. HIGHLIGHT

An LSM operation in Côte d'Ivoire employed six women as drone operators in its security department in 2022. This represents 86% of the total drone operation workforce. It resulted from the opening of a drone academy in the country that delivered recognized certificates for drone piloting. The digital department has also recruited women as data analysts and data scientists (S. Younga, personal communication, 2022).

FINDING 6

Large numbers of new businesses and indirect jobs are being created.

Most new technologies in the mining sector are introduced to either complement or reinforce the use of existing technologies or are completely new. The World Economic Forum (2017) projected that over the next decade, digital technologies could generate over USD 425 billion in value for the mining industry, society, and the environment; reduce CO_2 emissions by 610 million tonnes; and improve worker health and safety.

Table 6 shows that the adoption of new technologies in the mining industry has had a significant impact on other existing technologies and on non-mining businesses, with ripple effects on employment in those sectors.

Only 2 out of the 16 technologies in the table resulted in a decrease or replaced the use of existing technologies. In these cases, value and jobs were lost or were transferred to new industries. This was the case with the adoption of small smart electronic appliances (such as tablets), which slowly replaced the need for computers, printers, and other related electronic consumables. Similarly, the advent of 3D printing might replace the need to procure and stock spare parts for mining equipment.

Out of the 16 technologies examined, 3 new technologies complemented the use of already existing technologies or equipment. The wider use of drones did not replace existing differential GPS but rather embedded these technologies. Similarly, not all mines replaced their entire traditional equipment with autonomous assets. Many are using both in parallel. These technologies created new business opportunities and new jobs, although they may also have slowed down the demand for existing technologies and, subsequently, related employment.

Eleven out of the 16 technologies listed in the case studies were found to be completely new to mining operations. They created new businesses and job opportunities that were not typically associated with mining, although they may have been already in use in other economic sectors, e.g., all the sensors (cameras, radar, LiDAR, etc.) mounted on a dump truck to make it autonomous were completely new products and therefore were not replacing any existing technologies.

TABLE 6. Impact of new technologies on existing technologies

№	New technologies	Impact score
1	Drone	Complement to differential GPS
2	Connected wearables	New
3	High-precision GPS	New
4	RFID & RTLS	New
5	Tablets/smartphones	Reducing demand for paper usage/printer and consumables
6	Software using AI to recommend decisions	New

№	New technologies	Impact score
7	Software using AI to take autonomous decisions	New
8	Data warehousing, business intelligence	New
9	Advanced process automation	New
10	Robots, humanoid	New
11	Autonomous mobile fleet	Complement traditional equipment
12	Autonomous fixed asset	Complement traditional fixed asset
13	Immersive devices (VR, AR, MR)	New
14	Additive manufacturing (3D Printing)	Reducing demand for small spare parts
15	Cloud computing	New
16	5G	New

Source: Author, based on data gathered for this study.

The development and deployment of new technologies in the mining industry have undeniably increased the demand for digital services, such as internet and communication networks, cloud services, and development platforms. These have created demand for (a) new technology companies that can develop and provide such solutions to mining companies, (b) new consulting and service providers that can help mining companies integrate and use these technologies, and (c) new training providers to upskill or reskill mine workers on how to use these technologies safely and effectively.

These developments have stimulated indirect job creation in companies that employ engineers, technicians, consultants, trainers, and other skilled workers to develop, deploy, and maintain the new technologies, as well as other professionals, as support functions for their businesses.

FINDING 7

Local economies in emerging mining economies are taking limited advantage of the value created by this technological transformation.

The adoption of new technologies taking place in the mining industry today is creating a significant number of jobs and value, both direct and indirect. However, much of this is not being captured by the local economies of emerging mining economies, either via manufacturing or sourced from local suppliers, including sales and support.

As presented in Table 7, the study shows that in emerging mining economies, 40% of new technologies are not being sourced locally. Furthermore, those that have been sourced from local suppliers represent less than 10% of the volume purchased. Out of the 16 technologies identified, 11 were not manufactured locally.

TABLE 7. Distribution of new technologies sourcing and manufacturing per origin

New technologies	% sourced from local supplier (sales & support)	% manufactured locally
Drones	Very low (<10%)	Very low (<10%)
Connected wearables	No (0%)	No (0%)
GPS	Very high (>70%)	No (0%)
RFID & RTLS	No (0%)	No (0%)
Tablets/smartphone	Very high (>70%)	No (0%)
Software using AI to recommend and/or make decisions	Very low (<10%)	Very low (<10%)
Data warehousing, business intelligence	Very low (<10%)	Very low (<10%)
Advanced process automation	Very low (<10%)	Very low (<10%)
Robots, humanoid	No (0%)	No (0%)
Autonomous mobile fleet	Medium (30–50%)	No (0%)
Autonomous fixed assets	No (0%)	No (0%)
Immersive devices (VR, AR, MR)	No (0%)	No (0%)
Additive manufacturing (3D printing)	No (0%)	No (0%)
Cloud computing	High (50%–70%)	No (0%)
5G	High (50%–70%)	No (0%)

Source: Author, based on data gathered for this study.

There are several reasons why the local economies of emerging mining economies are only capturing a limited share of the value created by the technological transformation. These include, among others, the lack of capital and of a highly qualified workforce, insufficient investment in research and development (R&D) and in manufacturing capabilities in these technologies, insufficient policies to promote innovation and start-ups, and the small size of the domestic (or even regional) markets.

Developed countries generally host more R&D activities due to the presence of advanced educational institutions, corporations with larger R&D budgets, and supportive government policies. This allows them to be at the forefront of developing and implementing new technologies. Global automotive R&D spending in 2021 was estimated at EUR 137.5 billion (82% from the European Union, Japan, and the United States) (European Commission: Joint

Research Centre, 2022), while the leading mining companies in Africa generated USD 46.58 billion in 2021 (Statista, 2023).

Advanced mining economies generally have more robust education systems and a larger proportion of the population with tertiary education or specialized training. This leads to a larger pool of workers with the skills needed to implement, operate, and maintain new technologies.

To stimulate investment, governments in advanced mining economies could design policies such as subsidies, tax breaks, or regulatory sandboxes that allow for the testing of new technology to promote home-grown initiatives in R&D with a view to developing new technologies.

FINDING 8

Efforts still need to be made to offset the negative impact and capture more value from new technology ecosystems.

Mining companies face organizational challenges while transitioning to new technologies, especially toward more autonomous fleets. The reality is that there are not enough open positions over time to absorb the workforce made redundant, and there are other stakeholders to onboard, such as workers unions, local communities, etc.

Several options are being considered by mining companies to offset the impact of the introduction of new technologies on their workforce. These include

- natural attrition by not backfilling open positions
- early retirement for workers nearing the end of their careers
- reskilling workers for a redesigned role (e.g., from truck operators to autonomous truck operators)
- reskilling workers to be transferred to other mines or departments
- layoffs as the last solution (none of the companies in the case study has implemented this option)

In June 2019, Rio Tinto introduced Australia's first nationally recognized qualifications in automation. Accredited by the Training Accreditation Council (West Australia), the new modular courses offer a pathway to emerging jobs in automation. They are designed to upskill workers in analytics, robotics, and IT—key areas needed to succeed in an industry increasingly based on science, technology, engineering, and math (STEM). Rio Tinto is contributing up to AUD 2 million to the development of the curriculum (MiHR, 2020).

BOX 9. HIGHLIGHT

While the introduction of automation-related qualifications represents a significant step in preparing the workforce for future industry demands, it is important to address the gender disparities that exist in STEM fields, especially in robotics and automation. Globally, women are underrepresented in STEM-related careers, comprising only 29.2% of the STEM workforce in 146 nations evaluated in the Global Gender Gap Report (World Economic Forum, 2023), compared to nearly 50% of non-STEM occupations. This imbalance is particularly stark in fields like robotics, which are traditionally viewed as male-dominated domains.

According to the International Labour Organization (ILO), breaking gender barriers in technology, particularly robotics, is crucial to ensuring that women are not left behind in the future workforce (ILO, 2024). Women's participation in robotics has been limited due to cultural perceptions, gender stereotypes, and the lack of targeted training and encouragement for girls and women to pursue these fields. However, with automation becoming increasingly central to industries like mining, there is a significant opportunity to promote gender equality by intentionally designing programs such as training, scholarships, mentorship programs, and targeted recruitment efforts that encourage women's participation in robotics and related fields.

In 2022, Anglo American launched an extensive program on information and communications technology (ICT) across more than 100 schools around its mining sites in South Africa. The initiative aims to equip thousands of students and local community members with essential digital skills for the modern workforce. The program focuses on setting up technological infrastructure and devices at all participating schools, offering ICT training to boost digital literacy, and providing an online platform to engage students. It also includes continuous support to ensure the program's long-term success and sustainability (AngloAmerican, 2022).

Table 8 shows how governments, universities, and mining companies are already collaborating to develop initiatives aimed at improving skills development and local value creation.

TABLE 8. Summary of some actions conducted by governments and mining companies to improve skills development

Actions	Target	Description
ICT Program to improve digital literacy and skills (free wi-fi, laptop, training content, etc.) (Anglo American, 2022)	Local communities	Installing technology infrastructure and devices in all the schools; providing ICT courses and training; student engagement platform to support primary and secondary learners.
Vocational education and training programs to capture new direct jobs (Turner, 2018)	Workers and students	Qualification program with accreditation in new technologies in autonomous control and remote operations.

Actions	Target	Description
Centre for Innovation in Mining and Mineral Beneficiation at the Indian Institute of Technology (Moore, 2023)	Multiple stakeholders	This institute works with mining companies, universities, and other organizations to develop and test new technologies.

Source: AngloAmerican, 2022; Moore, 2023; Turner, 2018.

5.0 Policy Recommendations

The policy recommendations are informed by insight gathered from the case studies and from industry expert interviews. They are intended to help governments and companies harness the potential of new technologies both now and in the future. However, as there is no one-size-fits-all approach when it comes to policies combined with the fact that impacts are not homogenous across countries, governments should conduct country-specific studies to identify priority areas for intervention.

TABLE 9. Policy recommendations

Policy objectives	Description
Monitoring and assessment of policy performance	
Elaborate and follow up data-driven strategies	**For policy-makers and policy influencers:** • Government, with the participation of key stakeholders (ILO, non-governmental organizations, chamber of mines, mining companies, unions, etc.), should set up information systems to capture accurate information on labour dynamics to follow up on the evolution of the situation and make informed decisions. • Mining companies' activity reports to the government should include the disclosure of new technologies used by mining companies and the managing of impacts on their employees.
Local labour market (direct and indirect job creation)/local content	
Design informed data-driven policies	**For policy-makers:** • Countries to set up labour observatories/commissions for the mining labour market in collaboration with industry stakeholders to map the occupations that are being impacted by new technologies and follow up closely on the evolution of the situation to mitigate impact with a focus on local communities, especially on women and other traditionally underserved groups in these communities.

Policy objectives	Description
Capture local direct jobs created by new technologies by preparing the following: • Immediate workforce, especially in mining-related fields, by training students, by adapting their curricula to the current and the future industry requirements • Future workforce (primary and secondary education)	**For policy-makers:** • Adapt school curricula and create specific programs in collaboration with stakeholders to train future workers for short-, mid- and long-term needs. Work in partnership with tech providers to enable students to practice certain software programs that are being adopted by companies. Promote women's and girls' participation in such programs. • Education systems and training institutions must focus at an earlier stage on data and digital literacy, a core competency required for most jobs of the future. Additionally, they need to place much more emphasis on STEM subjects. Digital literacy should be considered a fundamental skill taught to children. It must be integrated as a core element of school education, both in the curriculum and in how lessons are delivered, separate from the instruction of specialized ICT, technology, and computer science subjects. (Committee for Economic Development of Australia, 2015). This is already the case in Australia, where STEM learning is integrated into basic literacy (IGF, 2023). **For mining companies:** • In collaboration with all stakeholders, mining companies can develop qualification programs with accreditation to enable mining engineers and technicians wishing to switch to new occupations (data science, data analysts, etc.) to benefit from accelerated training. • Provide continuous learning to upskill workers in order to empower them to pursue other careers. • Entrepreneurial initiatives. Create equal opportunities for women to be part of upskilling programs.
Capture indirect business (e.g., UAV drone assembler) and jobs created by technologies (Example: drone developer, drone maintainer, autonomous software developer, etc.)	**For policy-makers:** • Run region-specific studies on new business opportunities unlocked by the adoption of new technologies (such as smart device production/ assembly) to guide investment in this area to create local businesses and jobs. • Encourage technology providers to employ local workforce for marketing new technologies and implementation in mining companies. • Create national or regional technology innovation parks to encourage technology suppliers to establish a local presence (by partnering with local suppliers) and build up technology transfer to progressively create a local and competitive ecosystem.

Policy objectives	Description
Increase the employability and transferability of workers at risk of being displaced (such as production & clerical occupation) to other departments and/or industries by providing new skills needed in the digital era.	**For mining companies:** • Provide continuous learning to upskill workers to empower them to pursue other careers and or entrepreneurial initiatives.
Safety and productivity	
Enhance safety and productivity through new technologies	**For policy-makers:** • Government should set guidance and encourage the utilization of technologies that improve safety, such as collision avoidance systems, asset and people tracking systems, etc. **For mining companies:** • Invest in network connectivity to enable the implementation of people- and asset-tracking systems, equip tele-remote operation to ensure safety.
Communities	
Establish a "new deal" with communities, from employment in the operations to entrepreneurship in other relevant activities (IGF, 2024b), including investing in digital infrastructure and digital skills in mining communities.	**For mining companies:** • Manage expectations for job placement in the mine operation. Create opportunities for local communities in other businesses with a focus on women and other underserved groups. • Share connectivity infrastructure with local communities to enhance their participation in the digital economy and support digital literacy among mining communities. Offer tailored support for women and other traditionally underserved groups to improve their digital literacy and connectivity. • This can include setting up digital centres or hubs that provide internet access and training facilities, offering tailored programs aimed at equipping local communities with the digital skills necessary to participate in the digital economy (IGF, 2024b). **For policy-makers:** • Accelerate local content programs to capture more economic value for local economies. Set quotas, targets, and promotional programs for the participation of women and other underserved groups.

Policy objectives	Description
	• Embed digital infrastructure and skills training in national development plans, particularly in regions with mining operations. As part of such plans, policy-makers can offer tax incentives and subsidies for mining companies that share their digital infrastructure with local communities, thereby facilitating broader access to digital services and improving community resilience (IGF, 2024b).

Source: Author and contributors.

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Appendix A. Indirect Occupations Emerging From the Development of New Technologies

TABLE A1. Indirect occupation emerging from the development of new technologies

New technologies	Indirect occupation observed outside mining companies
Drone	• Drone pilot/operator • Drone engineer • Drone software developer • Drone technician • Drone payload specialist • Drone data analyst • Drone operations manager • Drone sales and marketing • Drone researcher • Drone regulations and policy specialist
Connected wearables	• Wearables training specialist • Wearables health advisor • Wearables data scientist • Wearables product designer • Wearables app developer • Wearables marketer • Wearables technician • Wearables data analyst • Wearables safety inspector
GPS	• GPS software developer • GPS hardware engineer • GPS consultant • GPS training provider • GPS marketing specialist • GPS technician • GPS data analyst • GPS safety inspector
RFID & RTLS	• Data analyst/interpreter • System integrator • IT support specialist • Training and education providers • Consultants

New technologies	Indirect occupation observed outside mining companies
Tablet/smartphone	• Mobile application support specialist • Mobile device management administrator • Mobile device training specialist • Mobile data management analyst • Mobile security consultant • Mobile accessories and device support
Software using AI to recommend decision	• AI project manager • Data quality analyst • Change management specialist • Business process analyst • Data privacy officer • Software validation specialist • IT infrastructure manager • AI governance consultant • AI system trainer
Software using AI to take autonomous decision	• AI data analyst • AI system auditor • AI system trainer • AI risk manager • AI process optimization consultant • AI decision support analyst • AI change management specialist • AI system security analyst • AI governance advisor • AI system maintenance technician • AI data quality analyst • AI business analyst
Data warehousing, business intelligence	• Data quality analyst • Data integration specialist • Business intelligence project manager • Data analyst • Report developer • Business intelligence trainer • Data warehouse tester

New technologies	Indirect occupation observed outside mining companies
Advanced process automation	• Process optimization analyst/consultant • Change management specialist • Maintenance planner • Training coordinator • Data analyst • Risk analyst • Business process analyst
Robots, humanoid	• Automation consultant • Data analyst • Robot maintenance technician • Training coordinator • Quality assurance specialist • Automation support technician
Autonomous mobile assets	• Autonomous technology consultant • Fleet management specialist • Safety supervisor • Data analyst • Training coordinator • Quality control specialist • Data security analyst
Autonomous fixed assets	• Autonomous fixed asset insurance adjuster • Autonomous fixed asset parts supplier • Autonomous fixed asset repair shop • Autonomous fixed asset testing laboratory • Autonomous fixed asset consultant
Immersive devices (VR, AR, MR)	• Immersive software developer • Training coordinator • Visualization specialist • Safety and emergency preparedness trainer • Immersive technology consultant • Quality assurance tester • Data visualization analyst • Maintenance and support technician • Data analyst
Additive manufacturing (3D printing)	• 3D-printing software developer • 3D-printing hardware engineer • 3D-printing training specialist • 3D-printing marketing specialist • 3D-printing safety consultant

New technologies	Indirect occupation observed outside mining companies
	• 3D-printing repair shop • 3D-printing testing laboratory • 3D-printing consultant
Fibre optics	• Fibre optic cable manufacturer • Fibre optic cable supplier • Fibre optic cable testing laboratory • Fibre optic cable training company • Fibre optic cable repair shop company • Fibre optic cable technician
4G	• 4G network operator • 4G network supplier • 4G network testing laboratory • IT support specialist/consultant • Data analyst • Software developer • Telecommunications consultant • Network infrastructure provider • Cybersecurity analyst • Cloud services provider

Source: Author, based on data gathered for this study.

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