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INTERGOVERNMENTAL FORUM
on Mining, Minerals, Metals and
Sustainable Development

NEW TECH, NEW DEAL

Technology Impacts Review

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New Tech, New Deal: Technology Impacts Review

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EXECUTIVE SUMMARY

1. INTRODUCTION

Advances in technological change in the mining industry are an integral part of the Fourth Industrial Revolution, leading to increasing automation of certain operational tasks and production processes and the application of intelligent networks able to connect various parts of the value chain. As a result, we expect mining processes to be smarter, leaner, more efficient, more flexible labour-wise and arguably more sustainable.

But the advent of disruptive technologies in the mining sector is nothing new, though it has yet to experience the level of disruption already faced by sectors like manufacturing, telecoms, and finance. What is different today is that changes are occurring at a speed and scale never seen before.

Only a handful of business leaders or governments are currently focused on anticipating and understanding the extent of opportunities and challenges that such systemic changes are expected to bring. Unaddressed, the increased adoption of disruptive technologies can pose major social and political risks in host countries and can threaten mining companies' social licence.

This report looks at the key drivers of technological change in the mining sector and the likely impact those technologies will have, in particular in the areas of labour and skills. It concludes with preliminary thoughts about the types of policies that might address the impacts of new technologies on the relationship between mining investment and local host communities along with host countries.

2. KEY EMERGING TECHNOLOGY TRENDS

The wave of technological change facing the mining sector has a few key drivers, including:

- The need to improve the health and safety environment for mine workers.
- The need to reduce (existing) operating costs and to improve productivity of assets and efficiency of operations, in the face of global economic slowdown, thinning margins and pressure on cash flows.
- The need to reduce costs of asset development as ore grades and accessibility decline while upfront capital costs rise.

More fundamentally, change is occurring because rapid innovations in a variety of fields—such as geographic information systems (GISs), artificial intelligence, cheap sensors, 5G wireless and big data processing—have suddenly allowed for cost-effective synergistic applications in ways that are revolutionizing the way mining is done.

Technologies being developed and adopted in the mining sector can be classified in the following categories:

(i) **Enablers of digitalization**, i.e., technologies that allow digital data collection about all aspects of operations—in huge volumes and in real time—and relay them to operating machinery and/or central controllers (e.g., smart sensors, connected wearables, GPS navigation programs and drones).

(ii) Technologies that act as **integrators or trackers of big data**, aimed at enhancing the performance of mining processes and solving complex problems (e.g., the Internet of Things (IoT), blockchain).

(iii) Technologies that **optimize operations and processes**, mainly through the use of big data and robotics (e.g., machine learning, data analytics, automation, remote operation, digital twins).

(iv) Technologies that **improve mining processes** (e.g., use of renewable power generation technologies; water management technologies).

(v) Other types of technologies that may impact local procurement (e.g., additive manufacturing).

3. IMPACTS

The impacts of new mining technologies are difficult to precisely quantify: "new mining technologies" are in fact a suite of very different innovations and applications, each of which will have different sorts of impacts. As well, every given technology will have impacts that are highly context-specific, playing out differently in different types of operations and locations. That said, there are some predictable aspects of those impacts:

- **New technology will improve productivity:** EY (2019b, p.9) anticipates an overall improvement in productivity between 9 per cent and 23 per cent as a result of digitalization and other technological innovations.
- **Technologies will have varying impacts:** Automation for instance, has positive impacts on health and safety, efficiency and productivity. But it will also have a mix of positive and negative impacts in terms of employment.
- **Some jobs are more at risk than others:** In the face of technologies like automation, repetitive and manual tasks—concentrated among lower-paid, lower-skilled, and less-educated workers—are at serious risk of obsolescence, while higher-skilled tasks such as those linked to the analysis of data, digital planning or remote centre operations will be created.
- **Gender-related impacts:** Men are more at risk on account of their larger share of employment in physical and manual jobs. As a result, they are likely to be disproportionately affected by the changing skill needs of the digital transformation. More opportunities will be created for women.
- **Uptake, and thus impact, is inherently context-specific:** Geological conditions (ore grade, depth of mines) and geographical location of mines are determining factors in investment decisions for disruptive technologies.
- **Size of mines will also affect the rate of adoption:** Large-scale and mega-mines have more financial means to invest in more advanced technologies than mid-sized or smaller mines. While higher uptake would be expected of larger firms, research shows that the latter face greater barriers associated with risk-aversion and organizational barriers that influence the adoption of unproven technologies.

- **Impacts will vary according to countries' development level:** Advanced and diversified economies are better able to absorb shocks from negative impacts. Many are home to tech-providing companies providing solutions to innovating mines. Less-developed and more resource-dependent countries, on the other hand, will find it more challenging, and impacts will be more visible in the national accounts and labour statistics.

4. IMPACTS ON LABOUR

This review focuses primarily, but not exclusively, on technologies that affect the labour force. These types of impacts are among the most significant from a sustainable development perspective, given that employment, and employment-related procurement, are among the most significant benefits that mining investment brings to host countries and communities.

The face of the labour market in the mining sector will change fundamentally: job categories will evolve, and skills requirements will change. These will create new and better opportunities for high-skilled labour but will also lead to challenges for those whose jobs will be replaced by machines.

We expect the following dynamics to influence the future of work in the mining sector as a result of technological changes:

- The changing nature of jobs. There will be dynamic gains and losses in different segments of the mining workforce.
- The changing working environment, with the growing ability of machines and connected items to work autonomously and a shift for more agile, experimental working styles.
- The need for education and training systems to adjust accordingly. Academic institutions are responding to the evolving needs of the mining sector by reviewing their curricular and research agendas and by facilitating work placements to better enable real-work exposure in a wide variety of dynamic operating conditions.

Trends in the adoption of technologies will have the following competing effects on employment.

(i) On the one hand, as disruptive technologies substitute for some types of tasks, the major risk is the extent of the job destruction effect, leading to displacement of workers. This is expected to occur mainly in low- to medium skilled occupations, where tasks are manual, repetitive and predictable.

(ii) On the other hand, technological changes will also create new jobs, including in areas thus far unknown. These are expected to be for mid- and highly skilled labour, performing tasks that require ingenuity and judgment.

(iii) Between these two effects a large number of tasks will be restructured and/or modernized, calling for skills adaptation, retraining and upskilling of labour.

(iv) Certain jobs will be centralized in single operating centres and will be delocalized outside host countries of operations.

(v) There will be a capitalization effect, as an increasing number of technological firms supply the mining sector, leading to new prospects for employment in those firms to increase.

(vi) Labour market dynamics in developed and developing countries will determine uptake and impacts on employment.

(vii) Indigenous communities will be disproportionately affected by the changing skill needs of the digital transformation, given their strong representation in the industry.

4.1 THE CHANGING ROLES AND NATURE OF FIRMS

New technologies can reshuffle mining value chains, disrupting both existing business models and the traditional roles and relationships among mining companies, their customers, their suppliers and even competitors. Some changes may include:

(i) The operational structure of the mining industry itself will change: many companies have already switched from owning capital equipment to leasing them. Others outsource parts of their operations to contract suppliers.

(ii) New types of operators, such as tech providers or automotive manufacturers, may become strategic investors in mining projects.

(iii) Universities, R&D centres of excellence and technological hubs, which will play a more prominent role in providing innovation ideas, solutions and high-tech services to the value chain.

(iv) Technological innovation will come from new fields such as biochemistry, bio-engineering and computer science. These disciplines have so far been outside the traditional core competence of the mining sector, implying a need to either bring new areas of expertise on board, form strategic partnerships, or purchase/license new technologies developed by others.

5. MOVING FORWARD: WHERE DO WE GO FROM HERE?

This report focuses for the most part on trends in technological innovation and the expected impacts of those trends, in particular on labour and skills. In closing, it briefly considers the next line of questions: what to do about the challenges and opportunities presented by those trends and impacts?

Five sets of policy options are briefly explored that governments and mining companies might consider in seeking to address the disruptive impacts of new technology.

5.1 INCREASING FOCUS ON SKILLS DEVELOPMENT

The development and application of new technologies in the mining sector require different competencies in the labour market. Successful adaptation to a new working environment will depend on the learning evolution of the labour force. The following conditions are required to address knowledge and skills challenges:

1. Skills development programs will require adjustments to enable workers to embrace the technological shift in the general education system, including by providing data and digital literacy at an early age, fostering more scientific subjects like science, technology, engineering and mathematics (STEM) in school curricula; integrating foundational skills as compulsory subject matters to promote critical thinking, creativity, digital skills and new management skills.
2. Skills development programs will need to educate the existing workforce to the new world of work, through innovative training programs and methods and retraining/ reskilling tools, both of which are critical for a smooth a transition toward new types of tasks.
3. Lifelong training is key to continuously upskill workers and empower them to pursue other interests and careers.
4. The very nature of careers is changing, with job- and career-hopping becoming more frequent. The prospect of engaging in lifelong careers will diminish, and skills development programs will need to continuously train employees in “transferable” skills to allow for smoother transitions.

5. The new work environment will require succeeding in the ability to shift to new management systems. Nurturing innovation and new technology require adapting skills and capabilities of staff to better work together, away from the traditional siloed approach.
6. Talent retention within the industry will be key. The mining industry is in direct competition with other sectors for talent, many of which have an edge in terms of technological adoption, given that the mining industry has been lagging behind. Regular skills updating and certification programs can in part address the growing skills shortages to fill the demand for sought-after knowledge in areas such as digital technologies and STEM fields.

5.2 INCREASING FOCUS ON SOME TYPES OF LOCAL CONTENT POLICIES

One way to address the potential loss of benefits arising from rolling out new technologies in mines is to think of new ways to foster local content to create more value. There are at least three salient types of local content opportunities that governments typically seek from mining companies. These are:

- Direct employment of locals: This focus would try to partially offset the reduced employment impacts of new technologies by employing more locals at both existing and newly created jobs. Training and upskilling need to be part of the requirements to prepare the workforce for the forthcoming changes.
- Procurement of local goods and services: There are a number of well-known strategies for boosting local procurement, from supplier development programs to unbundling contracts so locals can bid more easily.
- Local processing of mined materials (beneficiation): Although the history of policies to encourage downstream local processing of materials is replete with instructive failures, where success is possible, more local processing would be another path for replacing the benefits formerly derived from mining-related employment of locals.

5.3 FOCUS ON COMMUNITY ECONOMIC DEVELOPMENT

An obvious way for mining companies to address the loss of local employment-related benefits is to focus on supporting community economic development in the affected communities. A major set of challenges revolves around ensuring that any efforts are in fact in line with the priorities of the affected communities. If funds are to flow through governments instead of directly through mining companies, there are various challenges in ensuring the money gets to those that need it in the form of effective projects.

A specific form of community economic development involves the sharing of existing mining infrastructure (e.g., roads, rail, water treatment and supply, Internet) or sharing new infrastructure triggered by innovation in processes with the affected communities.

5.4 NEW ARRANGEMENTS BETWEEN HOST GOVERNMENTS AND MINING COMPANIES

The changing circumstances brought on by new technologies may lead to efforts to change the institutional, fiscal and legal arrangements by which mining companies and governments interact. For instance, there may be a temptation to increase taxes or royalties levied on mining firms that employ fewer people. Such a strategy assumes that new technologies create significant and sustained profit streams to support higher taxes. However, this is not certain, as upfront investments are very high and improved productivity does not necessarily guarantee higher profits, since in the long run rents will get competed away and the new technologies will simply become a prerequisite to staying in business.

Another possibility may be to rethink government ownership of mining resources. Such strategies would seek to derive more national benefits from the resource. The result would depend on mines being competitive in global markets, so that the state does not end up subsidizing operations. Several options are available, including increased state-controlled shares, or by entering into contract arrangements along the lines of the production-sharing agreements that exist in the oil sector. Governments may also seek to promote national champions, which could be privately owned large companies or state-owned companies.

5.5 NEW TECHNOLOGY AS PART OF THE NEW DEAL

New technologies have impacts far beyond reductions in the labour force. It is possible that some of the beneficial impacts of new technologies could help offset or compensate for other negative impacts from reduced local employment and procurement. Examples include technologies aimed at improving the environmental footprint of the mining industry, such as water-saving technologies or energy-efficient technologies.

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1.0 INTRODUCTION

Technological advances in the mining industry are an integral part of the Fourth Industrial Revolution (WEF, 2017), characterized by more productive machines and automation of certain operational tasks, digitization, greater and faster connectivity, and the application of intelligent networks across all parts of the value chain. We expect mining processes to be smarter, leaner, more efficient and more flexible in terms of employment, and arguably more sustainable.

Technological innovation has accentuated the growth in productivity and efficiency on a scale never before experienced. It has an immense potential to increase global incomes and the quality of life of many people across the world (Schwab, 2016). At the same time, it raises legitimate concerns of deepening inequality and potential labour market disruptions, owing to the looming jobless growth caused by labour-substituting technologies (Brynjolfsson & McAfee, 2014).

Although technological innovation is nothing new, the mining sector has yet to experience the type of disruption already faced by other sectors like manufacturing, telecommunications, and finance. What is different today is that the type and pace of change are occurring at a speed and scale never seen before (Schwab, 2016).

What is potentially game-changing is that these dynamics will not only radically transform the face of the mine. They will profoundly transform the way people live, work and relate to machines and to their workplace (Marr, 2018). More fundamentally, it will revolutionize the established relationships between the industry (mining, suppliers) and host countries (governments, local communities, other non-state actors etc.) (WEF, 2016b).

Only a handful of business or government leaders are currently focused on anticipating and understanding the extent of opportunities and challenges that such systemic changes are expected to bring. More worryingly, even fewer are thinking and designing sustainable solutions to embrace opportunities and manage the likely negative impacts. Unaddressed, the increased adoption of disruptive technologies can pose a major social and political risk in host countries and can threaten mining companies' social licences (Conference Board of Canada, 2018).

Managing these dynamics will require more than a focus on technological innovations. It calls for new approaches and enhanced partnerships to leverage the best of artificial intelligence and the best of human intelligence. This compels a holistic approach to transformation, which will need to be designed, implemented and monitored by a range of actors, working collectively to:

(i) Mitigate the potential negative socioeconomic impacts of the various types of technologies.

(ii) Take advantage of new opportunities unlocked by technological innovation to create more value.

(iii) Work together to adapt capabilities and skills of the labour force and other economic actors to adapt to modern technologies.

(iv) Adapt the institutions and policy environment to foster partnerships across industries (among mining industries and between mining and non-mining industries), between the mining industry and the local communities and between the mining industry and public authorities, to manage the transition together and better capture potential opportunities.

2.0 KEY DRIVERS AND BARRIERS OF TECHNOLOGICAL CHANGE

Globally, the mining industry has lagged behind other industrial sectors in embracing major technological innovations (EY, 2017b). While production techniques have modernized over time, the changes have not been fundamentally disruptive. In recent years, there has been a noticeable change in approach, in part to catch up with other industries, in part because it has become a business imperative, but more fundamentally because rapid innovations in a variety of fields—such as GIS, artificial intelligence, cheap sensors, 5G wireless, big data processing—have suddenly allowed for cost-effective synergistic applications in ways that are revolutionizing the way mining is done.

2.1 KEY DRIVERS OF TECHNOLOGICAL CHANGE

The following are key driving factors of technological innovation in the mining sector:

(i) **Reducing Risks to the Health and Safety of Workers**

Some mining operations can take place in extreme environments and/or in distant locations McKinsey and Company (2018). Moving operators to the mine face (whether by flying them in, moving them underground, or from shaft to face) is time-consuming, expensive and can be dangerous for workers' health and safety. Therefore, any technology that can minimize the presence of workers at complex and deep mining operations or at remote locations will contribute to improving their safety conditions and hence reduce risks of accidents and fatalities—a critical concern for mining companies and workers alike (WEF, 2017).

(ii) **Reducing (Existing) Operating Costs, Improve Productivity of Assets**

External factors, such as market volatility, unpredictable commodity cycles and the slowdown of growth in the global economy have put the mining industry's cash flows under acute pressure, making increased efficiency of operation an imperative. New technologies offer mining companies new avenues to manage operating costs when faced with such challenges (Conference Board of Canada, 2018).

Also, much of the technological innovation aims at driving up production volumes and boosting productivity, aiming for leaner and more efficient production and organizational systems.

(iii) Reducing Costs of Asset Development

There are still large mineral deposits to be explored and developed globally. However, costs of asset development are more significant for frontier assets. This has to do with rising upfront capital investments, increasingly remote location of new assets, and difficult access or depth of resources deposits, among others. Technological solutions are a way to reduce the cost of development for these assets (Deloitte, 2017).

Given the large upfront capital investments expected, successful adoption of cutting-edge technology is, however, conditional on the economic and technical feasibility of investment projects. Expected returns will be affected by (among other things):

- Expected increases in productivity (e.g., ability to mine lower-grade ore bodies at a competitive rate and at longer haul distances from the mine face).
- Expected increase in the lifespan of the project (i.e., ability to improve the extraction rates in maturing mines).
- The value of the resource deposit (investment more likely for high-value ores).
- Characteristics of the resource deposit (e.g., other things being equal, highly variable deposits are poor candidates for full automation; extremely deep deposits are good candidates for automation/electrification).
- Costs of upfront investments (retrofit are usually more costly than greenfield investments).
- Social, economic and political cost of replaced labour as well as new labour required.

(iv) Rapidly Aging Workforce, High Retirement Rate and Subsequent Rising Wages

In advanced and emerging economies, the mining sector is facing a rapidly aging workforce and an increase in anticipated retirement rate. It is estimated that in 1980, there were on average across OECD countries 20 people aged 65 and over for every 100 people of working age (20–64). This figure reached 28 in 2015 and is expected to almost double between 2015 and 2050.

As the workforce gets older, the retirement rate increases. For example, in a survey conducted by the Canadian Mining Industry Human Resource council mining companies indicated that about 20 per cent of their workforce would be eligible for retirement in the next five years, with significant spillover impacts on operational continuity, organizational know-how and operational experience (EY, 2017d).

These dynamics in turn are translating into large wage premiums due to skill shortages (including low uptake of post-secondary programs). Those are seen as additional factors prompting decisions to adopt new technologies.

(v) Reducing Costs of Technology Development

The cost of technology development and adoption is falling faster when compared with other costs such as labour, making it more affordable to industries (China Briefings, 2016). Additionally, many parts of the mining cycle are already well-suited to the integration of market-ready technologies (e.g., data optimization, automated vehicles, high-risk applications, drones for exploration, manual tasks suited for substations, etc.). These represent low-hanging fruit for rapid technological adoption. However, it is acknowledged that some segments of the mining industry may transition more quickly, as well-tested technology opportunities emerge commercially.

(vi) **Changing "First-to-Be Second" Attitude: Mining is catching up in digital intensity**

Generally, companies who are first movers in implementing new technologies bear a significant amount of risk (WEF, 2017): these are financial (if technologies are untested, they may be difficult to finance) but also regulatory, as they may not be approved by regulators if there are uncertainties regarding the technology's performance. Those risks can cause significant project delays.

Traditionally, despite the fact that many mining companies had innovative ideas about process improvements, many preferred to remain "the first to be second" (Hilton, 2019), i.e., to implement new technologies only once those were tested, costs went down and approval processes significantly improved. In that sense, first-commercial implementation had already happened in some mines or elsewhere in the economy, and it was seen as an advantage for the industry. Adoption risk was lower and benefits could be demonstrated (Meyers Norris Penny, 2011).

However, the "first-to-be-second" attitude is now changing quickly, with significant increases in technology spending observed around the world. The industry recognizes the pressing need to innovate, in part because of the growing competition from tech companies (Leach, 2014).

(vii) **Environmental Performance**

The mining industry is faced with rising domestic and external pressures to adapt and implement more environmentally friendly operational practices. This is not only becoming an investment imperative (Jagannathan, Ravikumar & Sammon, 2018)—the so-called environmental, social and governance (ESG) criteria—but also seen as crucial to enhancing the overall environmental footprint of the industry, in line with sustainable development commitments. As a result, mining industries are increasingly adopting green technologies across their supply chains in an effort to reduce water and energy consumption, greenhouse gas emissions and recycle wastes among others (El-Kassar & Singh, 2018).

2.2 MAIN BARRIERS TO TECHNOLOGICAL ADOPTION

There are a number of obstacles that slow or prevent adoption of new technologies in the mining sector including:

(i) **Disrupting existing value chains:** New technologies may disrupt—or face barriers from—long-established value chains. Long-term contracts or established procurement methods may hinder or slow mining companies' ability to pursue innovations within their operations.

(ii) **New safety challenges:** Rapid integration of new technologies may create hazards for workers not accustomed to working with them (e.g., failure rates of new technology, reliability, interoperability and connectivity issues in mine environments). They can create unintended challenges for mining investments (Eldridge, 2017).

(iii) **Managing labour transitions:** As mentioned later in this report, challenges may arise when striking the balance between managing the transition toward a smaller workforce and filling labour gaps without losing the sector's licence to operate in communities that depend on mining jobs.

(iv) **High upfront costs:** Upfront costs of some technologies may hinder adoption until the sector can develop a better understanding of new financing models for high-tech applications.

(v) **Standard, costs and regulations:** Interoperability is a key issue in mining applications, as connected technologies come from a suite of providers (Gleeson, 2019c). As well, the implementation of proper codes and standards—along with effective mining regulations—will be critical to managing the rate of diffusion of these technologies.

(vi) **Disrupting existing value chains—political economy dynamics:** Despite the economic rationale for the adoption of technologies, political economy can potentially block the adoption of technological innovations. Where there are expected socioeconomic losses from the adoption of new technology, local communities or host governments may work against change. Local communities can react by strongly objecting to project development, through union demonstrations, site blockages etc. Governments can react by tightening regulatory frameworks to force mining industries to provide or guarantee local economic benefits, through tighter local content requirements. Alternatively, mining companies may unilaterally refrain from adopting the most efficient technologies, anticipating these sorts of reactions, especially in the context of a retrofit of existing operations.

3.0 KEY EMERGING TECHNOLOGY TRENDS

Emerging technologies, and in particular "disruptive" technologies—i.e., innovations that displace current technologies and reshuffle the way the business environment operates—are becoming more prominent in the mining sector (McKinsey Global Institute, 2017c). The past decade has seen an acceleration in the pace of technological innovation and adoption, expected to have impacts unlike anything seen before in this sector, catching many businesses and governments unaware.

From artificial intelligence and the rise of chatbots, to robotics and the Internet of Things (IoT), emerging technologies and innovative business models are driving huge paradigm shifts that many established industries and governments are simply failing to grasp (EY, 2019).

Mining companies and governments in the 21st century need to look beyond the world as they know it today. The choice is simple—either they drive the debate regarding technological disruption or they run the risk of being disrupted: if they don't manage change, it will come back and hit them hard.

3.1 WHAT ARE THE KEY EMERGING TECHNOLOGIES?

Before assessing the impacts of technological changes, it is important to have a clear understanding of the different technologies being developed and applied in the mining sector. As noted above, different technologies will have different impacts, some will cause challenges, notably for the labour market (EY, 2017c), but others will create significant opportunities that can be leveraged to create more value in the economy at large.

Disruptive technologies relevant for the digitalization of the mine have the following characteristics:

(i) Access to big data,[1] i.e., databases that are too large to be processed by humans. Big data is critical to provide fast, accurate and comparative analysis. Combined with advanced analytics and real-time information management, it can significantly improve mining efficiency and minimize risks for workers and machine breakdown.

[1] Big data is a field that treats ways to analyze, systematically extract information from, or otherwise deal with data sets that are too large or complex to be dealt with by traditional data-processing application software. It is associated with the "5 V" concepts:

a) Volume i.e., the quantity of data generated and stored.
b) Variety i.e., the type and nature of the data—text, audio, video etc.
c) Velocity i.e., the speed at which the data is generated and processed to meet the demands and challenges that lie in the path of growth and development. Big data is often available in real-time.
d) Veracity, i.e., the data quality and value. The data quality of captured data can vary greatly, affecting the accurate analysis.
e) Value: The size of the data determines the value and potential insight, and whether it can be considered big data or not.

(ii) An enabling environment that supports large data sharing, functional networks and digital platforms able to share the information in real time.

(iii) Availability of cost-effective and well-performing digitalized ecosystems with secure, predictable and high-speed connectivity.

Table 1 provides a typology of emerging technologies relevant to the mining sector and their key characteristics.

TABLE 1. A TYPOLOGY OF TECHNOLOGICAL INNOVATION RELEVANT TO THE MINING SECTOR

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
1. Enablers of big data				
Sensor technologies	Sensors are elements that convert physical quantities into electrical signals transferred to the controller. They can be: inductive, capacitive, optical, magnetic, ultrasonic, etc. Their function is to detect presence, level, pressure, temperature, flow, pH, etc., and communicate it to the system.	• LIDAR (Light detection and ranging) sensor technology in autonomous vehicles • Remote operations and precision planning: Smart sensors connected to automated vehicles/helmets and a range of other tools can better help control/remotely monitor equipment and infrastructure; identify obstacles • Predictive maintenance: Smart sensors combined with algorithms can help predict breakdowns; detect anomalous conditions/ installations and maintenance • Sensors to detect the grade, hardness and size of ore coming into the processing facilities.	Improves labour productivity	Ensures accurate and cost-effective manufacturing. Using digital twin applications, companies can perform simulations to determine efficiency and productivity of a future mine. Perform probability modelling—a major advantage when time is a decision factor. Help save time and money because weather and physical conditions are no longer obstacles

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Connected wearables	Allows interface between machines and humans to enhance productivity Designed to interact with humans in a shared workspace	• Personal protective equipment (PPEs) with built-in tag • Co-bots: Characterized by small size, versatility and are affordable in price • Touch technology • Captive pads • Helps detect fatigue and stress levels • Supervisory control and data acquisition	Employees equipped with those can better monitor/ navigate in complex environments; provide real-time data. PPEs can detect if the environment condition is safe for an operator.	Specialized connected devices used by operators to provide real time information; to observe, intervene and monitor operations Aimed at corrective, preventive and predictive maintenance Control and supervise operations from a distance Advantages: precision, strength and resistance
Drones (UAVs)	An unmanned aerial vehicle that can navigate autonomously, without human control or beyond the line of sight Equipped with GPS navigation systems and sensors to perform in-situ scanning, measurement and assessment	• Stockpile inventory and management • Mine monitoring and operation planning • Assessment before and after drilling and blasting • Hazard identification and mitigation • Geological mapping and surveys • 3D data output	Can replace labour in some applications (geo-surveys; site planning and monitoring) Can also enhance labour productivity and provide more accurate information to enhance decision making. Eliminate the hazards employees typically face while walking through dangerous zones, navigating active sites or climbing onto stockpiles. Can access areas that are difficult for humans to reach	Can reap significant productivity enhancements. Improves the overall efficiency of mines Provide accurate and comprehensive data of site conditions in a very short time Support better coordination among teams onsite and internationally, offering dynamic oversight of all operations Operate much faster than labour at lower costs. Potentially more beneficial for remote extraction activities

<table>
<tr><th>Type of technological innovation</th><th>Characteristics</th><th>Key applications</th><th>Potential impacts on labour</th><th>Wider impacts</th></tr>
<tr><td>GPS</td><td>A satellite-based navigation system that provides information, including the position of the satellite, velocity and the precise time of transmission.

GPS technology works in almost any conditions and is accurate to within 3 to 15 metres.</td><td>Helps in navigation, surveying, tracking. Frequently used in:
• Control of heavy machinery
• Control of bucket wheels and dozers
• Drill guidance
• Road grading and maintenance
• Fleet management systems for haul trucks and other vehicle tracking and dispatch
• Access and zone control for visiting vehicles
• Detecting dangerous driver behaviour
• Collision avoidance applications</td><td>Limited negative impacts

Positive impacts:
• Enhances worker productivity
• Improves safety of workers in use of equipment
• Reduces risks of injury and fatalities
• Increases security of workers
• Alleviates heavy workload by allowing the streamlining of operations
• Improves drivers' behaviour (such as reduce hard-braking and fast acceleration etc.)</td><td>Enhances overall productivity (incl. by streamlining operations)

Lengthens assets lifetime (less wear and tear due to optimized asset management; early maintenance reminders etc.)

Reduces fuel budget</td></tr>
<tr><td colspan="5">2. Users of big data</td></tr>
<tr><td>Machine learning (ML)</td><td>Use large data sets, artificial neural networks and algorithms to detect patters, process data and learn autonomously how to make decisions

A type of machine learning that processes a wide range of data resources (that may be too large to be processed by humans) to produce more accurate results

Also includes universal quantum computers</td><td>Those analytical techniques can be applied to solve real-life problems, i.e.,
• Descriptive: Identify patterns of behaviour
• Predictive: Anticipate what will happen
• Prescriptive: Provide recommendations on what to do to achieve objectives
• Clustering: Individual data sets with common characteristics—or with ability to create synergies—are assembled

Applications include:
• Image classification
• Facial recognition
• Voice recognition

Quantum computers augment data crunching capabilities by orders of magnitude.</td><td>Positive impacts:
• Highly efficient and can perform multiple tasks simultaneously and provide predictions instantaneously
• Processes large amount of data with great accuracy
• Able to reproduce human decision making, but more quickly
• Can detect anomalies/defaults/weaknesses and allow better stock planning
• Enhance supply chain optimization

Negative impacts:
• Task automation will reduce demand for labour
• Certain specific types of jobs will disappear due to redundancy</td><td>Value of ML lies in organizational abilities to harness it

Biggest impact likely to be in supply chain management and in particular on activities such as:
• Maintenance and service intervention
• Smart CAPEX
• Procurement and spend analytics
• Inventory and parts optimization
• Yield optimization
• Logistics networks and warehouse optimization
• Sales and demand forecasts</td></tr>
</table>

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Advanced analytics	Objectives to be achieved: decisions and actions based more on data analysis and less on experience and intuition. Four key characteristics of big data: Volume: Treatment of large volumes of data Range: Different forms and sources of data Speed: Allows real-time analysis Accuracy: The information will facilitate decision making	• Enable end-to-end tracking and communications and real-time supply and demand management • Descriptive analytics • Predictive analysis: Can pinpoint requirements; address bottlenecks; determine output • The data collected (geological; metallurgical; operational) will allow the use of 3D visualization and digital twinning • 3G/4G connectivity can send data in real time	Positive impacts: • Predictive maintenance reduces equipment downtime and facilitates life-cycle management • Requires digitally skilled labour Negative impacts: • Semi-skilled labour performing tasks in traditional ways will be made redundant.	Will dramatically reduce costs across the value chain, from exploration to logistics. Improve efficiency: Can create simulations to precisely prepare plan and schedule operations
Automation: Hardware automation/ Autonomous assets	Predicted to redesign traditional occupations such as drill operators, surveyors, field geologists; increase the demand for remote vehicle operators with greater skills in contemporary data and digital technologies	• Autonomous haulage systems • Operators remotely controlling multiple rigs simultaneously • Mine automation system • Telematics (condition monitoring) to avoid downturn • Vehicles without drivers and monitored from a distance	Positive impacts: • Improved safety for workers in environments that are complicated for human beings (high level of toxicity; extreme temperatures; extreme depth; low levels of oxygen) • Increased demand for remote vehicle operators with greater skills in contemporary data and digital technologies Negative impacts: • Significant reduction in employment for repetitive/ predictable and manual tasks	Improved efficiency and drilling precision, reduced human error in transport

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Robotic process automation (RPA)	A combination of artificial intelligence and automation that is able to sense and synthesize vast amounts of information and can automate entire processes or workflows, learning and adapting as it goes	• Process automation and configuration • Graphical user interface (GUI) automation • Advanced decision systems	Some tasks are at risk of being replaced by machines (back-office functions; corporate services, data management and planning) Can make employees more efficient by freeing up time for more analytical work and data analysis, rather than performing routine tasks	It makes mining processes more accurate, more liable and more consistent. It improves productivity of mining operations because process cycle times are much faster compared to manual operations.
Software automation	Machines match and outperform human beings in a range of activities, including those requiring cognitive capabilities	• Software guiding remote controlled excavators, teleoperated vehicles etc. • Software to guide drivers toward most optimal routes to reduce transportation time	Positive impacts: • Improve performance and productivity • Reduce errors • Improve quality and speed • In advanced countries, can help offset impact of a declining share of the working-age population Negative impacts: • Inbuilt in hardware automation and likely to accelerate impacts on labour • If skills are not available, will pose added challenges to domestic labour	Software automation tools help mining operators maintain real-time control over operations for better safety and efficiency.
Digital twin	A digital twin is a virtual simulator of mining operations. It is a carbon copy of the digital world.	Management can use the simulator to manipulate a huge number of variables over a given time period to see how changes will affect both up- and downstream processes	Requires highly skilled labour to interpret and manage tools If skills are not available, will pose added challenges to domestic labour	It is an optimization tool that allows for improved efficiency. It facilitates decision making in an objective way to optimize production processes. It incorporates data and digital information into the real-world environment.

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Cloud computing	Technological model that allows firms and individuals to access a set of computer resources on demand and in a personalized manner	• Data management • Collaborative platforms and virtual workspace • Requires strong cybersecurity	Requires highly skilled personnel to manage collaborative platforms Some tasks likely to be restructured due to use of shared platforms/virtual workspaces	Storage makes information accessible from anywhere Advantages: Cost savings; storage and security; easy access; automatic updates and customization
3. Integrators/ trackers of big data				
Internet of things (IoT) and Industrial Internet of Things (IIoT)	IoT is the connection of objects such as computing machines, embedded devices, equipment, appliances, and sensors to the Internet. The goal is to make all devices transfer data to a network without human intervention and, therefore, be more intelligent and independent. Industrial applications of IoT: IioT devices are more resistant since they have to work under extreme conditions without breaking down and are usually located in places that are difficult to access.	• Automate maintenance and operations of machines • Standardize processes • Improve traceability and visibility • Move from preventive to predictive maintenance • Get real-time data and analytics	Ensures safety of people and equipment	Optimizes operations Increases safety Reduces costs Improves data and analytics

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Blockchain	A tamper-proof digital ledger that can document the provenance and characteristics of products, making information accessible to buyers at every stage	Areas where blockchain might be used: • Engineering, construction and handover of the mine site: Can make transactions traceable during the complex processes of managing regulations and standards, ensuring trust and work compliance • Compliance and mining lease management: Approval of documents, contracts, audit, management of reserve flows • Supply chain management: can be used to track materials in the mining value chain from the blocks to the concentrate, to metal; manage procurement contracts, invoice reconciliation etc. • Mineral provenance and responsible sourcing	Some tasks likely to be made redundant due to automatic tracking (accounting; auditing; data management etc.)	Guarantees quality and authenticity Ensures traceability Can help increase transparency along the mineral value chain Can support moves to improve mineral valuation
Radio Frequency Identification (RFID) and Real-Time Location System (RTLS) tags	These are small devices, similar to a sticker, which can be attached or built into any object. They contain antennas which can receive and respond to requests by radiofrequency from a transceiver	RTLS tags are used to automatically identify and track location of people and objects, within a building or in an area. Types of technologies include: infrared and ultrasound	Improves safety of personnel on mine sites and allows the monitoring of operators' movements in difficult environments	Efficiency gains: (i) This technology, combined with the electronic product code (a chip), can improve the tracking of products along the supply chain (ii) Critical for logistics to monitor stock and better manage supply chains

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
4. Process improvers				
Water-neutral processing/ water-saving technologies	Technologies meant to: • Minimize the use of water in mining operations • Minimize/ eliminate risk of pollution • Recycle water for mining and/or other uses	Types of technologies include: • Evaporation control • Closed-loop water recycling • Dry tailings water disposal • Dry separation • Non-aqueous processing	Indirect impact on employment: through improved access for non-mining sectors (can potentially create jobs)	Impact on water usage (public good) Reduces footprint of the mining sector on the environment Conservation of water Potential to share benefits of saved water with communities or other economic sectors
Tailings management and recovery	Tailings management is a complex issue that encompasses the technology used to de-water the tailings, materials handling, and water management, as well as the design and risk management of the tailings storage facility	• Management and storage of tailings using concentrators • Tailings thickening, to reduce environmental risks and decrease seepage • Efficient recovery of process water • Reduction of slurry and water pumping • Dry tailing storage	Limited direct impacts on employment	Improved environmental footprint of industry Reduced emissions of effluents and dusts Reduced risks of accidental bursts and collapse Site rehabilitation and aftercare Metal recovery or reprocessing
Smart energy systems	Optimal energy management is key to increasing the competitiveness of industries in the face of increasing cost of supplies	• Renewable energy sources • Systems to manage energy generation (co-generation) • Systems to recover residual heat • Use of batteries	Limited direct impacts	To optimize energy systems and efficiency
Electric mining equipment	Battery-powered vehicles and equipment to replace fuel and diesel equipment	• Trucks • Drillers • Battery-electric haulage	Improved health conditions for workers due to lower GHG emissions and exposure to fine particles	Improves environmental footprint of industry Reduce GHG emissions Better heat generation Less noise pollution Cost savings (fuel a large share of costs) Improved and cleaner mine site logistics

Type of technological innovation	Characteristics	Key applications	Potential impacts on labour	Wider impacts
Biological technologies	Genetically manipulated bacteria or nanobots that mine at the molecular level	• Mines to look leaner and smarter, involving intelligent, mini-, micro-, and nano-machines • Use of fluids to dissolve rocks with more precision • Use of nano-robots	Increase safety of workers Will create new job opportunities from fields currently not related to mining Will further automation, therefore riskier for lower-skilled workers	Precision mining Increased efficiency and productivity at lower costs Use less energy Produce less waste and less impact on the environment
Innovative bio-mining and bio-mineralization technologies	Technology based in the collection of microorganisms from hydrothermal vents	Applied to the extraction of lower-grade ore deposits, mine by-products and recycling of man-made products (geologically uneconomical resources)	Can create new jobs as these will open up new activities	Allows for recycling of products Improves environmental footprint
5. Other technologies				
Additive manufacturing: 3D and 4D printing	A series of parts manufacturing technologies that fundamentally differ from conventional subtractive machining processes. The different additive processes each possess unique advantages in materials and applications.	The processes can broadly be categorized into the following eight groups: (i) Binder Jetting; (ii) Directed Energy Deposition; (iii) Direct Write; (iv) Material Extrusion; (v) Material Jetting; (vi) Powder Bed Fusion; (vii) Sheet Lamination; (viii) Hybrid Technologies. Different processes utilize different materials/forms and can result in different properties.		Possibility of manufacturing prototypes and to replace spare parts, at a relatively low cost (allows firms to save on time and shipment costs

Source: Author's research.

For the purpose of this study we classify disruptive technologies into the following four categories:

3.1.1 ENABLERS OF DIGITALIZATION

(i) Augmented intelligence technologies such as **smart sensors**, which allow people and organizations to collect digital data about all aspects of operations in huge volumes and in real time and relay them to operating machinery and/or central controllers (Gartner, 2018). Examples include smart sensors; connected wearables; satellites and drones.

In the mining sector, smart sensors and wearables are applied across various parts of the value chain to support other technologies in boosting the operational performance and efficiency of mining processes. Goldcorp, for instance, uses smart sensors in its Éléonore mine in Canada to lower energy costs, by turning off lights and power when people are not in a particular area (CISCO, 2015). Such technologies improve worker safety during blasting operations and help manage the air filtration systems to direct fresh air to where it is most needed. Goldcorp assessed that it managed to save between USD 1.5 million and USD 2.5 million per year on energy as a result of air filtration management (World Economic Forum, 2017).

(ii) **Connected wearables**, such as tablets, watches, vital sign trackers, glasses and helmets, are used to augment the ability of the workforce and foster seamless communication by allowing mine and plant management to capture critical real-time information (EY, 2016). These technologies enable remote expert assistance when those are required as well as conduct real-time diagnosis and guidance to solve problems and repair damaged equipment.

A number of mining companies in Australia, such as Rio Tinto, BhP Billiton, Anglo American and Newcrest Mining have equipped their employees with technologies such as Smart Caps aimed at monitoring brainwaves in order to measure fatigue. These were first introduced for truck drivers and machine operators to reduce the risk of injuries that could be caused by fatigue (WEF, 2017).

(iii) Assisted intelligence technologies such **Global Positioning Satellite (GPS**) navigation programs: In open-pit operations, some mining companies have introduced GPS technologies on blasthole drills and electric cable shovels to obtain more accurate and real-time three-dimensional visualizations of the location of the drill point or the shovel tracks. Information thus obtained allows operators to precisely steer the drill from blasthole to blasthole, maintain a desired shovel grade, or face position from a distant location (Worldsensing, 2018).

(iv) Unmanned aircraft systems such as **drones** are flying mini-laboratories. They can be used for a range of purposes including geological data collection, site planning, rock face inspection, real-time blast control, collection of water samples, assessing weather and environmental conditions and safety monitoring. They are also versatile and can be fitted with a wide range of accessories that can then perform site and equipment inspections from angles and areas that are more challenging for humans to access.

Data collected is instantly transmitted to other systems and operating centres. Mining companies like Freeport-McMoRan are already using drones to monitor and evaluate blasting operations. Similarly, in Canada, experience suggests that unmanned aerial vehicles survey teams can operate up to 20 times faster than ground-based teams of surveyors in the mining sector (Conference Board of Canada, 2018).

3.1.2 TECHNOLOGIES THAT ACT AS INTEGRATORS AND/OR TRACKERS OF BIG DATA TO ENHANCE PERFORMANCE

These types of technologies are aimed at improving the efficiency of mining operations (EY, 2016). Their use is expected to grow at an exponential pace in the forthcoming decade, and allow the mining environment to be more integrated for real-time problem solving. They include technologies such as:

(i) **(Industrial) Internet of Things** platforms, which are based on the interconnection of smart devices, services and systems. The goal is to permit the transfer of data from all devices to networks with limited human intervention. This is meant to improve efficiency, minimize costs, optimize equipment management, increase asset utilization and improve real-time performance monitoring of operations.

The advent of 5G networking is expected to unlock the significant potential and improve the performance of IoT platforms. In 2015, Deloitte (2015) estimated that the incremental global contribution of IoT technologies was expected to more than double between 2014 and 2018, rising from USD 400 billion to USD 1 trillion. This is expected to double again by 2020 to reach USD 1.9 trillion.

(ii) **Blockchain** is a tamper-proof digital ledger used to document the provenance and characteristics of products, making information accessible to users at every stage (Devan, 2018). It improves trust and transparency and allows the automatic detection of fraud, which in turn, reduces the risk of round-tripping and double-financing. The diamond company DeBeers developed a blockchain platform to track progress of its diamonds. The platform, called Tracr, creates a digital trail for each diamond (Mining Technology, 2018a). It established an “end-to-end baseline of trust” that helps overcome challenges of authenticity and compliance. Blockchains can be similarly used for smart contracts, which enable buyers and suppliers to monitor the fulfillment of contractual obligations (detect breaches for instance) and therefore trigger necessary payment actions without human involvement.

Blockchain technologies are already in use in other industries like supply chain management where they are used to track containers during shipping and in the retail sector, where Walmart can now retrace mangoes to their original source within 2.2 seconds (EY, 2019). In the mining sector, blockchains are particularly being used to track responsible supply chains downstream, notably to better manage the sourcing of minerals from conflict-affected areas.

3.1.3 TECHNOLOGIES THAT OPTIMIZE OPERATIONS AND PROCESSES, MAINLY THROUGH THE USE OF BIG DATA.

Some technologies allow machines to understand, learn, and then act on information gathered to adapt actions as circumstances change (PwC, 2017). These types of technologies are likely to be omnipresent in the next 10 years, with a wide range of functions and uses. They have the ability to optimize operations, making machines perform cognitive functions traditionally associated with human minds, such as perceiving, reasoning, learning and problem solving.

Specific technologies include:

(i) **Machine Learning and Data Analytics**

Machine learning enhances the capacity of machines by using algorithms to quickly and accurately analyze very large data sets, learning from the relationships discovered there. The result is an improved ability to perform the sorts of descriptive, predictive and prescriptive tasks traditionally performed by humans (Muro & Whiton, 2019).

One example of this is predictive maintenance, in which in which millions of data points on past machine performance and repair are combined with real-time data from existing machinery—for example fed by sensors that detect anomalies in temperature or vibration—to assess the remaining useful life of components, to better plan for repairs, maintenance and interventions (Deloitte, 2018a).

Such technologies are crucial to reduce downtime and operating costs while improving production yield. They allow better organization of stocks and orders.

The combination of **data analytics** with algorithms is a powerful tool that mining companies are using to make more strategic decisions, based on insights from data. For instance, companies can use such analysis to (Accenture, 2016a):

- Control mineral characteristics through drill and blast enhancement and improved blending to help meet required output
- Better plan mine operations based upon predictive alerts
- Enhance asset management through predictive assets maintenance
- Improve workers' safety through fatigue monitoring.

(ii) **Automation/ and or remote operation**, through the use of data, software and person-less machines. There are different types of automation processes:

(a) **Software automation tools** help mining professionals maintain real-time control over operations for better safety and efficiency. These tools can perform jobs like creating reports and therefore provide more time for professionals to focus on solving more complex problems, further enhancing efficiency. Some examples include tools such as modular information management solutions, like those developed by the Swedish company Sandvik, which are coupled with autonomous assets. These technologies have been used in the development of a new underground mine in Mali (see Box 1), which is the first fully purpose-built automated mine in the world. Two of such systems are:

- **OptiMine™**, which is an information system that offers a real-time view of underground mining operations, notably through a three-dimensional visualizer for the mine; a drill plan visualizer as well as other tools for drilling (Sandvik, n.d.a). It also provides accurate real-time location data for machines and equipment.
- **AutoMine™**, combines mechanized tools and equipment with other software to telemonitor and remotely control their use. It allows for autonomous operation of single pieces of equipment as well as entire fleets of trucks, loaders and drillers both underground and on surface (Sandvik, n.d.b).

BOX 1. SYAMA MINE, IN MALI

Originally developed by BHP as an open-cast gold mine in the 1980s, Syama in Mali was subsequently taken over by Randgold Resources and then by Resolute Mining in 2004. Since then, Resolute Mining has undertaken feasibility studies to design a new underground mine to supplement the open-pit operations (NS Energy, n.d.). It partnered with Sandvik to design a fully purpose-built automated mine, which has now been in operation since December 2018.

The Syama mine is located 300 km southeast of Mali's capital, Bamako. It has total reserves of 3 million ounces of gold, generating about 2.7 grams per ton, meaning that it is not an exceptionally high-grade ore body. However, it is very large (200 m thick and over 1 km long) and has an ore body that lends itself to sub-level cave mining, which involves a lot of repetitive activities. The partnership between Resolute Mining and Sandvik resulted in the implementation of a fully automated production system using technologies that Sandvik had tested elsewhere in the world, including the AutoMine® and OptiMine® systems (Cloete, 2019).

To address connectivity issues, guarantee digital communication, optimize traffic and maintenance schedules and to ensure that underground equipment is in constant contact with the control centres above ground, the company has installed a fibre-optic network throughout the mine.

According to the company, technology will significantly increase efficiency of the mine and improve safety. Given the nature of the ore body, to be profitable it was necessary to reduce the mine's cost profile. Automation resulted in a 15 per cent cost reduction, bringing down the cost of production from USD 881 per ounce down to USD 746 per ounce, despite upfront investments in autonomous equipment of a range of USD 10 million to USD 15 million. Over time, Resolute expects mining costs to be reduced by 30 per cent (Mining Technology, 2018b).

The Syama mine (which includes an open-cast and an underground operation) employs 1,500 people in total, mostly employed in the open-cast operation. Training programs have been designed for the local workforce so the latter can work with the more sophisticated machines and tools.

(b) **Robotic Process Automation (RPA)** tools, which perform repetitive tasks such as back-office finance operations and supply chain management. The next generation of RPA tools is expected to include cognitive technologies such as optical character recognition, natural language processing and generation to augment the efficiency of machines (EY, 2017b).

(c) **Hardware robotics and autonomous assets** are powered by artificial intelligence and machine learning. Automated equipment is able to replace manual human labour, although the assets still require remote control operation by human workers (see Box 2). Some of the fully automated technologies on the rise include ore truck driving, rock drilling, automated and driverless trains.

BOX 2. AUTOMATED ASSETS BEING DEPLOYED IN SOUTH AFRICA AND AUSTRALIA

An example is the ultra-low-profile mining machines (developed by CMTI Group), soon to be implemented at Sibanye Gold's Burnstone gold mine in Balfour, South Africa (Capital Equipment, 2018). The machine, which has a 7-hour battery, has a sweeper and dozer attached to and is equipped with a drill rig and mechanical breaker that can drill several holes simultaneously for conventional blasting. It can also be equipped with a remotely controlled laser scanner. The machine is easy to control and is equipped with track-based wheels that can navigate in difficult underground environments.

Australia has been the testing ground for automated assets, in part due to the remote geographical location of certain mines. At the open-pit Pilbara mine, operated by Rio Tinto in Western Australia, autonomous trucks are used to ensure 24/7 non-stop operations (Rio Tinto, 2012). The direct economic benefits have been a 15 per cent gain in productivity and efficiency with autonomous haulage in place for just 20 per cent of the operations. In 2018, the company operated a fleet of about 80 autonomous trucks and plans to increase its fleet to about 130 by the end of 2019, all remotely managed from its headquarters in Perth, 1,500 kilometres away from mining operations. This would represent 30 per cent of its fleet. The region of Pilbara in Western Australia hosts 75 per cent of the automated vehicle fleets in operation globally (Gleeson, 2019a).

In addition, Rio Tinto also piloted its first heavy-haul, long-distance autonomous train in 2018, able to carry about 28,000 tons of iron ore over a distance of 280 kms to the port of Cape

Lambert. The “AutoHaul” project uses 200 locomotives on 1,700 kilometres of track to transport ore from 16 mines to four port terminals in the Pilbara region (Kwan, 2019).

The company also runs fully automated drill systems across Pilbara and uses drones to measure stockpiles and assist with environmental maintenance activities. In Pilbara, BHP and Fortescue have also embarked onto similar technologies (Iannucci, 2018).

(iii) **Digital twin[2] applications** provide an immersive virtual environment through accurate, electronic and digital representations of the mining environment and operating facilities. Well-designed digital twins of assets significantly improve planning, management and decision making.

Digital twins combine data obtained from connected items such as sensors and wearables to other information such as product demand, inventory, maintenance and planning (Leonida, 2018). Together, these provide a platform for advanced analytics to reproduce, simulate, predict, and optimize mining processes and operating environments. This results in more efficient planning and management of operations over different time horizons. For example:

- Mining companies are able to simulate virtual “what if” scenario planning to test new methods of processing and production (Accenture, 2016b). Digital data, combined with technical characteristics and economic modelling, can help decide on the appropriate levels of spending on new capital and operational projects.
- Digital twin applications provide virtual visualization of physical mining locations. This has multiple advantages: it gives an overall view of the mining environment, which helps more precise analysis and decision making. It allows various specialists to work on different problems at the same time, which is not possible when done physically. It is an immersive constant training tool for employees (Leonida, 2018).
- Simulations enable deeper insight into equipment assets, allowing them to predict and prevent failures and to improve mine efficiency.

3.1.4 TECHNOLOGIES THAT IMPROVE MINING PROCESSES

Mining is one of the world’s most energy- and water-intensive industries—one of the main ongoing struggles therefore is to secure uninterrupted and cost-effective access to both resources. Today, growing concern over the environmental footprint of the industry is increasing the pressure on the industry to optimize its energy mix to reduce its GHG emissions and use greener sources. New technologies are therefore being used to “green” mines and minimize and optimize water usage.

Relevant technologies include:

(a) **Advanced process control**, such as the optimization of energy use in processes such as crushing; greater use of machine learning to map large amounts of accumulated real-time data on incoming material characteristics (grade, hardness, etc.) to improve the efficiency of operation.

(b) **The use of renewable power generation technologies:** In Chile, Barrick Gold has announced that by 2020, its Zaldívar Copper Mine will be powered with 100 per cent renewable

[2] The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object. Twins are linked to their real-world counterparts and are used to understand the state of the thing or system, respond to changes, improve operations and add value.

energy, which will enable the company to reduce GHG emissions by 350,000 tons annually (Benton, 2018).

(c) **Clean technology** to further reduce carbon emissions through the use of electric vehicles. This has the twin benefit of reducing greenhouse gas emissions and minimizing exhaust gases that must be vented—a particularly important health concern in underground mines.

(d) **Water-management technologies**, viewed both as a sustainable and a pressing issue, to manage risks of water scarcity, pollution and avoid conflicts. Mining companies face increasing supply risks due to water scarcity. Companies are therefore investing in process innovations to minimize water use and improve its management, notably through techniques such as closed-loop water recycling, evaporation control and dry tailings disposal.

As part of its Future Smart Mining Program, Anglo American aims to eliminate the use of fresh water from its mining processes, in particular in the separation and transport of ore and waste (tailings). Three innovations include closed-loop water recycling, evaporation measurement control and dry tailing disposals (Anglo American, 2018).

Mining companies also face environmental risks due to effluent leakages and toxic floodwater runoff resulting from severe climatic conditions. For example, in Viet Nam, flooding in 2016 arising from heaving rainfalls caused water to run off from 16 open-pit coal mines. This was a major cause of concern regarding the impact of toxic contamination on the health of the local population.

3.1.5 OTHER TYPES OF TECHNOLOGIES THAT MAY AFFECT PROCUREMENT

Additive manufacturing processes are transformative technologies for industrial production. They enable the creation of lighter, stronger parts and systems, reducing lead time for production and delivery. They can help produce specific spare parts on demand and tailored to the characteristics of what has to be replaced and significantly reduces downtime, as spare parts can be manufactured closer to the industry. They are more than just about products, and have the potential to revolutionize the manufacturing sector. Firms will be able to produce almost anything, within the boundaries of a single printer (EY, 2019) and a single location.

Some examples include:

(i) Mass customization of objects: a single machine will be able to custom-make products or prototypes, based on specific needs of any industry, including mining;

(ii) The development of 3D modelling software will significantly improve collaboration between procurement departments and product developers;

(iii) 4D printing, which adds an element of time to 3D printing.

Expected impacts are likely to be felt in maintenance services (including on people performing those services) and suppliers of procurement items (not necessarily in a negative way, because local suppliers will be able to acquire the technology to manufacture inputs closer to the market—"local" can become an advantage over "imported").

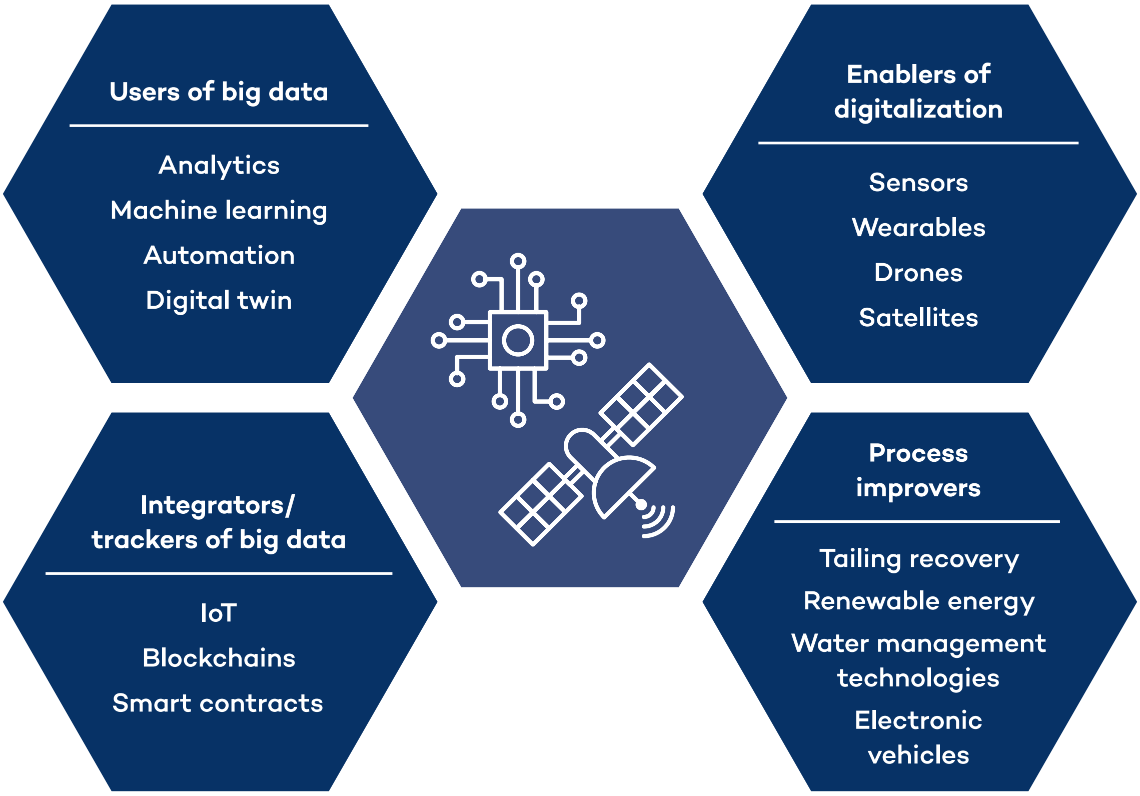

FIGURE 1. DISRUPTIVE TECHNOLOGIES: A VISUAL TAXONOMY

Source: Author diagram.

4.0 TYPES OF TECHNOLOGIES AND THEIR APPLICATIONS

When new technologies are being developed, there tends to be a lot of attention, speculation and promises about what those technologies can or cannot do. Of course, not all promises are likely to materialize, and there are often more questions than answers regarding their likely impacts, be they positive or negative (Gartner, 2018). For example:

- How does one distinguish the hype from what is actually commercially viable and sustainable in the long term?
- Within what timeframe can we reasonably expect such technologies to pay off (if at all)?
- What will be the speed of adoption and how fast will those be replaced for more advanced techniques?
- Are there substantial labour market changes at stake? If so, to what extent, what job categories are most at threat? Which types of tasks will change and what new opportunities are expected to be created?
- Will there be any (political or societal) obstacles to the adoption of certain types technologies?

Although the speed of adoption is very context-specific, there are nonetheless some trends that are emerging and spreading rapidly across the globe. As Figure 2 illustrates, all parts of the mining value chain have already embraced new technologies, enabling the mining sector as a whole to operate faster and more efficiently.

Types of technology	Enablers of digitalization	Technologies that use big data to optimize productivity	Data integrators and trackers	Process improvers and green tech	Additive manufacturing technologies
Exploration	Drones Spectre imaging GPS/satellite imaging Sensors Wearables Big data/ cloud computing	Autonomous assets Advanced analytics/ Machine learning 3D visualization	IoT	Biotechnologies Advanced process control Electric vehicles (EVs) Battery-operated drills Smart energy tech	
Mining operations (extraction)	Ore-sorting technologies Sensors Wearables Big data; cloud computing	Machine learning and data analytics; Autonomous assets (vehicles; drilling; blasting) Integrated drill/ blasts Digital twinning 3D simulation/ modelling	IoT Blockchain Smart contracts	Advanced process control Water-saving technologies Biotechnologies Tailing recovery EVs Smart energy tech	3D/4D printing (spare parts)
Mining processing	Sensors Wearables/ Mobile decision support Big data/ cloud computing Remote/ integrated operating systems	Robots/ Autonomous assets Data analytics Digital twinning	IoT Blockchain Smart contracts	Water-saving tech; Biotech; EVs Smart energy tech	3D/4D printing (manufacturing)
Logistics and Transportation	Integrated operating systems; Big data/cloud computing	Autonomous assets (trucks; trains; ports; ships) Digital twinning Machine learning	IoT Blockchain Smart contracts	EVs Smart energy techs	
Trading	Integrated operating systems	Autonomous assets (ships/ trucks/ train etc.)	IoT Blockchain Smart contracts		
End-to-end	Remote/ integrated operating centres	Integrated automation Digital twinning	IoT Blockchain Smart contracts		

FIGURE 2. EXAMPLES OF NEW/EMERGING TECHNOLOGIES ACROSS THE MINING VALUE CHAIN

Source: Author diagram.

At the exploration phase, for instance, the amount of data being collected digitally and the ability to combine it through digital twinning will significantly reduce the cost of exploration because more precise simulations will allow better planning and operations scheduling. When combined as well with other technologies such as sensors, data twinning will further help assess the profitability of projects as well as the efficiency and productivity of future mines (EY, 2017a). Information relayed will enable mining companies to analyze in greater depth the characteristics of the ore in the ground and run probability modelling, a critical advantage in making decisions about project development.

The processing phase is probably the one where most advances are being made at the same time. Sensors provide real-time data for more effective planning. They can also help companies manage their operations remotely. Predictive maintenance and automatic spare-parts replacement software can avoid or minimize equipment downtime while improving life-cycle management. The increasing use of autonomous equipment in blasting and drilling improves drilling precision and efficiency and reduces risks of worker accidents.

New technologies are increasingly being applied to the downstream part of the value chain to increase efficiency and productivity. Activities in areas including logistics, trading and end-to-end value chain management are using the IoT and digital twinning to optimize planning and scheduling, with the aim to significantly reduce costs, manage stockpiles and monitor on-time delivery (McKinsey Global Institute, 2016). For example, built-in GPS and detection technologies in vehicles can boost routing of delivery traffic from pit to port/shipping, thus improving fuel efficiency and reducing delivery times. The combined use of sensors can further improve monitoring and enhance both the performance of vehicles and the behaviour of drivers, in particular regarding stress and fatigue. Real-time applications can provide advice to drivers about traffic and best routes, as well as providing guidance regarding when to speed up or slow down. Minimizing vehicle stop time is cost-efficient, optimizes fuel consumption and reduces maintenance costs overtime.

4.1 WHAT TECHNOLOGIES ARE MOST LIKELY TO BE ADOPTED IN THE SHORT TO MEDIUM TERMS?

Despite growing efforts to embrace technological innovation across the globe, the mining industry seem to be only slowly catching up with other sectors, a situation which is rather surprising given the perceived opportunities (EY, 2017b).

One of the main reasons is that the context in which mines operate may not always allow for fast technological innovation. Based on specific geological conditions, adoption may be faster or slower. Other determining factors include the availability of digital infrastructure, the cost-benefit calculations of investments as opposed to expected returns given the quality of ore grades or quantity of resource endowments etc. Further, aversion to change may still create some reluctance within the industry's leadership to make rapid investment decisions (EY: 2017b).

In 2017, the consulting firm Accenture conducted a survey, looking at the technologies that are most likely to be embraced by mining companies in the next five years (see Figure 3). The survey highlighted the speed and readiness of technological adoption across various stages of the mining value chain by 2022 (Accenture Consulting, 2017).

	Explore/ acquire	Mine development	Mine	Ore processing	Logistics	Sales & marketing
Robotics and automation (mobile and fixed assets)*	42%	47%	54%	45%	33%	24%
Advanced process control	22%	31%	37%	41%	23%	17%
Drones/UAVs	32%	30%	41%	24%	19%	11%
Remote operating centres	30%	29%	41%	36%	22%	17%
Mobile/tablet use	35%	36%	31%	26%	37%	36%
Wearables	32%	37%	41%	30%	23%	25%
Integrating planning	33%	32%	28%	30%	29%	27%
Digital platforms (cloud, etc.)	28%	25%	27%	19%	36%	39%
Real-time visualization of data	36%	28%	35%	31%	27%	23%
Real-time analytics	33%	28%	38%	30%	29%	23%
Video analytics	34%	29%	29%	28%	24%	15%
Image analytics	39%	29%	33%	29%	17%	17%
Virtual simulation of physical environment	32%	34%	37%	30%	21%	16%
Artificial intelligence and cognitive computing	37%	40%	39%	18%	19%	15%
Social media	32%	32%	27%	30%	25%	20%
Cybersecurity	23%	24%	22%	22%	29%	47%
3D printing	34%	32%	26%	24%	38%	33%

** Robotics and Automation (mobile and fixed assets) refer to those instances where respondents have/plan to employ Robotics and/or Automation in each respective mining activity.*

10–19% 20–29% 30–39% 40–49% 50–59%

FIGURE 3. DIGITAL TECHNOLOGIES BEING ADOPTED MORE QUICKLY BY MINING OPERATIONS BY 2022.

Source: Accenture Consulting, 2017.

As highlighted above, most of the changes occur at the mine-processing phase. The top four technologies are not surprising: they are (i) robotics and automation (over 50 per cent expected); (ii) the use of unmanned vehicles and drones; (iii) the use of wearables and other connected items; and

(iv) remote operating centres, necessary to control all of the three other technologies (Accenture Consulting, 2017). Taken together, those are sufficient to reshape the organizational and operational structures within the mining industry and the relationship it will have with its employees, suppliers, local communities and host governments. But this is just the tip of the iceberg, considering the potential of technologies in the pipeline.

Indeed, miners are looking at more sophisticated and cutting-edge technologies in the medium term (Accenture Consulting, 2017), to maximize the benefits of the digital, automated and integrated environment, currently being put in place. The next phase of investments will deepen advanced process control systems, to create greater convergence and stronger horizontal connections across different processes within mines, and most importantly across the different parts of the value chain, from mines to markets.

Box 3 provides some more examples of technologies expected to have a ground-breaking impact on the way the industry functions.

BOX 3. TRENDS: GARTNER'S ASSUMPTIONS REGARDING TECHNOLOGICAL ADOPTION BY THE HORIZON 2030.

By 2020, the number of citizen data scientists[3] will grow five times faster than the number of expert data scientists.

By 2020, there will be more mainstream use of virtual software engineers to generate code.

By 2020, there will be more than 20 billion connected sensors and endpoints, and digital twins will exist for potentially billions of things

By 2020, 4% of network-based mobile communications service providers is expected to launch the 5G network commercially, although by 2022 they are not expected to reach the current geographic coverage of developed countries.

By 2021, 10% of new vehicles will have autonomous driving capabilities, compared with less than 1% in 2018.

By 2021, half of large industrial companies will use digital twins, resulting in a 10% improvement in their effectiveness.

By 2021, "swarm intelligence"[4] will be a core design element for at least 30% of firms deploying AI-enhanced systems.

By 2022, at least 40% of new application development projects will have artificial intelligence co-developers on the team.

By 2022, 70% of enterprises will be experimenting with immersive technologies for consumer and enterprise use, and 25% will have deployed them to production.

By 2022, more than 50% of all people collaborating in Industry 4.0 ecosystems will use virtual assistants or intelligent agents to interact more naturally with their surroundings and with people.

By 2023, 20% of firms will be budgeting for quantum computing projects, compared to less than 1% in 2018.

[3] Citizen data science is an emerging set of capabilities and practices. It enables users whose main job is outside the field of statistics and analytics to extract predictive and prescriptive insights from data. These users are called citizen data scientists.

[4] "Swarm intelligence" refers to the collective behavior of decentralized, self-organized systems, natural or artificial.

Quantum computing is an emerging trend with the potential for significant impact between 2023 and 2025

By 2028, storage, computing, and advanced AI and analytics technologies will expand the capabilities of edge devices[5], ranging from sensors to mobile phones and automated vehicles.

By 2030, blockchain will create $3.1 trillion in business value.

Source: Gartner, 2018.

4.2 TRENDS OF TECHNOLOGICAL ADOPTION GLOBALLY

This section collates additional examples of technological adoption. It provides insights about the uses and implications of new and emerging technologies relevant to the mining sector.

The examples below highlight different types of technologies being deployed across the world. For instance, companies like Gold Fields,[6] BHP and Anglo American have pioneered specific programs looking at technological innovation in their mining operations, to help them improve their productivity and efficiency.

In Africa, investment in automation is not new. In the Northern Cape of South Africa, the Finsch diamond mine has been operating fully automated "driverless" trucks in haulage loops for over 10 years (*Modern Mining*, 2018). In 2014, similar investments were made, notably in the greenfield Venetia underground diamond mine in South Africa's Limpopo province, where Anglo American invested in fully automated trucking loops, drills and haulage trains (*Modern Mining*, 2018).

The Kibali mine in DR Congo (Creamer, 2017) is an underground mine that has undergone significant investments to improve productivity through automation and mechanization. The mine's profitability, however, rests on the availability of affordable power. In that regard, the mining company invested in hydroelectric power to secure a reliable supply. The mine is equipped with an integrated, automated ore-handling and shaft system, the first of its kind in Africa. It includes features such as multiple driverless loaders that load and haul on a single haulage drive, and a smooth, high-strength roller-compacted concrete haulage surface, which improves haulage speed with minimal spillage. On the surface, drones are used for pit and stockpile measurements.

In DR Congo, Ivanhoe is developing its Kamoa/Kakula copper project, expected to become the second largest copper mine in the world. It is expected to be a highly mechanized underground operation (*Modern Mining*, 2018).

In Ghana, the modernization of the Obuasi mine (which had remained under caretaker for five years) by Anglo Gold Ashanti was made possible due to investments in more mechanized operations and by shifting to contract mining (*Modern Mining*, 2018). In 2014, this entailed reducing the workforce by 87 per cent (The Economist Intelligence Unit, 2014)—from 4,300 jobs when the mine closed temporarily for retrofitting, to 550 in the newly reopened mine (*Ghanaweb*, 2019).

[5] According to Jennifer Garfinkel of Gartner, "Edge computing describes a computing topology in which information processing, and content collection and delivery, are placed closer to [the sources and repositories of this information] . . . It tries to keep the traffic and processing local, with the goal being to reduce traffic and latency" (Garfinkel, 2018). Michael Wang states that "Edge computing draws from the concepts of mesh networking and distributed processing" and that the notion of edge content delivery has existed for many years (Wang, 2018).

[6] Goldfields has a Technology and Innovation plan clearly articulating its objectives and milestones.

In Latin America, Chile has been driving technological innovation in the mining sector for over a decade. Since 2008, Codelco, the state-owned copper mining company and the world's largest copper exporter, has operated 18 autonomous trucks at its open-pit Gabriela Mistral mine in the Antofagasta Region (Invest Chile, 2018).

In Chile, BHP has successfully tested a technology to detect driver fatigue (Yeomans, 2017). This technology called "Smartcap" is equipped with an electronic strip that sits on the driver's forehead. It is able to measure brainwaves that show fatigue. The sensors in the cap communicate wirelessly with a small unit in the truck's cabin warning the driver and supervisors.

The Minera Centinela mine in the Antofagasta Region is testing a new generation of drones that will be completely autonomous (Airobotics, 2018). These drones will draw maps and carry out volumetric measurements and topographic surveys. The data is connected to a data processing software to allow data analysis, planning and decision making.

Anglo American is using digital twins (Leonida, 2018) to boost the productivity and safety of its mine operations. At the Los Bronces mine in Chile, digital twins are used to track the performance of haulage. Similarly, the technology is being used to monitor the 500 km slurry pipeline in Brazil to prevent future leaks. To date, digitized technical equipment has led to a 30 per cent improvement in the business (15 per cent productivity improvement and 15 per cent cost savings) (Collins, 2018).

In Brazil, Vale has set up an Artificial Intelligence Centre (Mining Technology, 2019) to collect and analyze data from its projects, with a view to improving the efficiency of its infrastructure. One of the "high-impact" projects focused on predicting rail fracture on the Carajás railroad, where the most common and serious incidents occurred (Intelligent Mining, 2019b). The combination of data with analytics resulted in Vale saving USD 8 million at its Salobo mine, increasing the life of off-highway truck tires by about 30 per cent in one year (*Intelligent Mining,* 2019b).

In Canada, an increasing number of mines are using digital tools and technology to improve their productivity. At Glencore's Onaping Depth mine, digital systems are used to plan shift-level tasks, monitor task progression, and track delays and equipment availability (Hatch, 2018). The objective is to reduce operational variability and improve productivity, using an integrated people-process-technology approach.

In Central Asia, in Kazakhstan, the Kacharsky mine has invested USD 10 million into a new modular automated system for production processes, which it has integrated into the existing geographic information system (GIS) and enterprise resource planning system (Leotaud, 2017). The mine can be monitored in real time by sensors that can detect where changes should be made in the mining process to improve productivity. The government announced in 2017 that it will support digital technologies in the mining sector to prepare it for the Fourth Industrial Revolution (Leotaud, 2017).

5.0 IMPACTS

This section lays out the overall impacts expected from the adoption of new technologies, with the caveat that the impacts of the Fourth Industrial Revolution—in particular on employment— are challenging to predict with certainty. As well, the impacts of new mining technologies are difficult to describe at any level of generality.

As described above, “new mining technologies” represent a suite of very different innovations and applications, each of which will have different sorts of impacts. As well, the impacts of each are highly context-specific, playing out differently in different types of operations and locations.

That said, although it is hard to make quantitative forecasts, there are still some predictable aspects of those impacts, as follows:

(i) **New Technology Will Improve Productivity**

EY (2019b) explored the impacts of digitalization and technological innovation across the minerals industry value chain. The study anticipates a total overall improvement in productivity of between 9 per cent and 23 per cent due to the adoption of digital technology, with stages in the value chain such as mining operations estimated to achieve productivity improvements of up to 25 per cent (EY, 2019b).

Mines optimized for efficiency and productivity will reduce the sector’s overall energy use and GHG emissions, thus improving its environmental footprint.

(ii) **Different Technologies Will Have Varying Impacts**

The impacts of technological innovation are multidimensional: technological innovations are likely to have different implications, some more positive than others. Research estimates that by 2025, 30 per cent of commercial trucks will become autonomous. From a safety perspective, this would reduce accidents by between 70 and 90 per cent. Such autonomous vehicles are also expected to increase fuel efficiency by up to 40 per cent (McKinsey Global Institute, 2013).

However, the picture is starkly different from a labour perspective, where employment is expected to fall by between 80 and 90 per cent. In Canada, a recent report forecasts that 37 per cent of the workforce employed in the trades, transport and equipment fields in the mining sector will be negatively impacted by the adoption of autonomous vehicles (Conference Board of Canada, 2018).

(iii) Some Tasks Are More at Risk Than Others

The speed of technological adoption and the expected impacts will vary across different types of technologies. However, it is worth noting the obvious fact that technological change is not a matter of a homogeneous disrupter acting with uniform impacts. Some tasks are more at risk from some technologies, like automation, than others, and some jobs will be affected more than others—both negatively and positively.

Risks to employment are higher for occupations related to trades, transport and equipment operation. Research consistently finds that the tasks most likely to be threatened by technologies such as automation are those that are manual, repetitive and predictable, whose workers are also lower-paid, lower-skilled and less-educated. Although the number of jobs that will be lost is difficult to predict with certainty, occupations in the frontline for full automation include truck driving, rig drilling and blasting (Baggaley, 2017). In Australia, it is estimated that 60 per cent of mining jobs in certain regions are at risk of disappearing in the next 10 to 15 years as a result of technological advancement (Sparkes, 2016).

On the other hand, occupations expected to benefit the most from technological disruption include engineers, computer network technicians, software developers and data analysts (to name but a few). New jobs will tend to be filled by highly educated and skilled workers with the capacity for creating and critical thinking (Boy, 2013).

(iv) Uptake, and Thus Impact, Is Inherently Context-Specific

Different technologies are most suitable to different contexts. Australia is a leader in automated trucking in part because of its wealth of resources in open-pit settings in remote locations that require fly-in/fly-out workers with conventional hauling technologies. In 2015, a study estimated that by 2025, 80 per cent of Australia's professional drivers of road and rail vehicles would be replaced by automation (PwC, 2015).

Some technologies, like the optimization of crushing using sensors and machine learning, can be retrofitted to existing operations relatively easily, while others would require extensive system changes. The combination of electrification and automation is particularly suited to deep operations that would require costly air conditioning and venting of exhaust in convention operations.

(v) Size of Mines Will Impact the Rate of Adoption

Arguably, large-scale and mega-mines have more financial capacity to invest in advanced technologies compared to mid-sized or smaller mines. While one would expect higher uptake on the part of larger firms, they may face greater barriers associated with risk-aversion and organizational barriers that influence the adoption of unproven technologies. This is linked to the fact that they have traditionally been less engaged with tech firms, and more with engineering firms, who by nature, tend to implement projects, rather than provide innovative solutions, due in part to their limited involvement in R&D.

(vi) Impacts Will Vary According to Countries' Level of Development

Technological changes will affect developed and advanced countries differently (McKinsey Global Institute: 2017d). As a rule, rollout of new technologies is likely to be faster and more ambitious in advanced countries (and in particular in remote areas). These countries have a more diversified economic base and are well equipped with reliable and fast connectivity infrastructures, which greatly facilitate the adoption of newer technologies. Governments in advanced countries may also be less intimidated by rapid adoption, although they also face unique challenges, such as the need to support workforce transition in impacted areas. The mining sector already has highly integrated mining projects across the value chain, also easing technological adoption.

A country where digital infrastructure enabled faster adoption of automation is Australia, where investments were made right through to the logistics part of the value chain (Nieponice, Vogt, & Koch, 2019). This may not always be possible in other countries with infrastructure difficulties or with low-quality connectivity. Recent innovations in Mali (the Syama mine) and DR Congo (Kibali mine) were only made possible because the mines made significant upfront investments in IT infrastructure to secure connectivity that compensate for the gaps at the national level. This can impede investment decisions if costs are too high or not shared by governments.

In developing countries, greenfield projects are most likely to be embedded with advanced technology, while retrofits might have to be carefully negotiated due to the need to manage the transition between lost opportunities (in particular for labour and local procurement) and new opportunities, provided the requisite skills and capabilities are available. Failure to do so would pose serious threats to social and political stability. This is particularly important in lesser-developed countries that are heavily reliant on mineral resources and who are therefore likely to bear a heavier burden arising from technological disruption. Impacts are expected to be more significant on employment and on local economic development. In least-developed countries the impacts may be exacerbated, with even less scope to redeploy people in the formal sector due to the lack of other strong economic sectors.

5.1 IMPACTS ON THE LABOUR MARKET

Despite the fact that the key factors driving technological changes in the mining sector relate to improving worker safety and operational efficiency, rather than deliberate moves to save labour costs, there is no doubt that there will be implications for the labour market (McKinsey Global Institute, 2017b).

Disruptive technologies will permanently affect the labour market, in particular through a massive and fundamental reclassification of occupations and new job categories emerging in fields probably still largely unknown (World Economic Forum, 2016a). Skills requirements will change accordingly. While new technologies will create new and better opportunities for high-skilled labour, they will also lead to challenges for those whose tasks will become obsolete and replaced by machines and new production processes (OECD, 2019).

While the perceived benefits of technological innovation are relatively clear for the mining industry, issues are more complicated for policy-makers. The latter are often disconnected from technology debates and may not have a clear understanding of what changes are coming. This leaves them rather unprepared regarding how they should adapt their policies accordingly and/or manage the transition to prevent social and political crisis (International Labour Organization, 2018).

BOX 4. HOW LABOUR MARKET DYNAMICS EVOLVED IN THE MINING SECTOR IN THE UNITED STATES

Case #1: The coal sector in the United States

In the United States, the continued decline of employment in the coal industry is due in part to the use of more mechanized processes over the years. Employment in the coal mining industry was at its highest in the 1920s, when the sector employed around 785,000 people nationally. By the 1980s, employment had declined to about 242,000, a number which was further halved over just two decades—by 2000, the number of jobs had declined to 102,000. By 2015, coal mining had cut down 59 per cent of its workforce compared to 1980 (Saha & Liu, 2017).

However, during that same period, coal production grew by 8 per cent, to about 897 million short tons in 2015, while productivity rose from 1.93 short tons per miner hour in 1980 to 6.28 short tons per miner hour in 2015 (Saha & Liu, 2017).

The pace of automation marked a clear acceleration in coal mining when there was a shift away from underground coal mines in the Appalachian region to the open-pit mines (particularly in Montana and Wyoming) because surface mining[7] is less labour-intensive and more automated than traditional underground mining. Due to more efficient technologies and an increase in the production of surface mines, coal companies in the Powder River Basin in Montana and Wyoming could extract more than 11 times as much coal per employee hour as coal companies in the Appalachian Basin. This trend is expected to continue over the next decade, and the coal mining industry will likely lose even more jobs to automation. It is important to note that job losses due to automation do not occur gradually over time—they occur in waves, often a result of recessions and when new production techniques are introduced (Saha & Liu, 2017).

Case # 2: Primary metals producing sector (steel and aluminum) in the United States

As in the coal sector, employment in the primary metals sector in the United States has dropped significantly since 1990 (by about 42 per cent). Over the same period, production remained stable (except during the 2009 recession).

Data for employment in the primary metals-producing sector incorporates five subcategories: iron and steel mills, steel product manufacturing from purchased steel, aluminum production and processing, production and processing of metals other than iron and aluminum, and foundries (Smith, 2018).

As a result of the above factors, productivity increased significantly as a result of improved technology, which include not just machinery but also the way that factories have reorganized production, due to enabling technologies (Smith, 2018).

[7] Also known as mountaintop removal mining, in which miners use controlled explosions to open mountains and mine the newly exposed coal seams.

Case #3: Steel industry in the United States

A study published in the American Economic Review analyzed the impact of a new technology for producing steel—the minimill—on industry-wide productivity in the U.S. steel industry, using unique plant-level data between 1963 and 2002 (Collard-Wexler & De Loecker, 2015).

It found that there was a sharp increase in the industry's productivity as a result of this new technology. However, the steel industry laid off about 75 per cent of its workforce during the same period, which amounted to about 400,000 job losses (Collard-Wexler & De Loecker, 2015).

This dramatic fall in employment had far-reaching economic and social implications. For example, between 1950 and 2000, the size of the economy of Pittsburgh—once the centre of the U.S. steel industry—shrank dramatically. The city dropped from the 10th largest city to the 52nd largest, a major setback for the local economy.

While employment in the steel sector fell by a factor of five, output per worker grew by the same rate, and shipments of steel products continued to rise, making the sector one of the fastest growing manufacturing industries over the last three decades, behind only the computer software and equipment industries.

TRENDS AFFECTING THE LABOUR MARKET

We expect the following competing dynamics to influence the future of work in the mining sector as a result of technological changes:

(i) Labour market dynamics will determine net impacts on employment: As mentioned earlier, in advanced economies, one of the key concerns is the forthcoming labour supply shortages arising from the aging labour force, difficulties in recruiting labour to remote/fly-in/fly-out sites, and the rising costs of labour that goes with labour scarcity (PwC: 2018). Labour cost savings is a key issue in investment decisions. This was an important factor in Pilbara, Australia, when deploying automated vehicles in the mine.

However, in developing countries, the opposite dynamic is observed, with a growing population and a burgeoning youth segment (International Labour Organization, 2019). In that case, there is a key concern regarding the impact of such labour-saving technologies (such as automation) on the labour force, in particular in countries or regions where the mining industry is an important employer.

We are therefore more likely to see more mines with fewer jobs in advanced countries than in developing countries (World Economic Forum. 2016a). However, adoption across the industry is only a question of time, which arguably gives developing countries a buffer or a slightly wider window of opportunity to prepare the workforce through enhanced skills development.

As disruptive technologies substitute for labour, on the one hand, one of the most feared risks is the extent of job[8] destruction, notably through the disappearance of occupations whose functions will be mechanized and/or be replaced altogether, or through the displacement of workers, to be reallocated to different tasks, either locally or remotely (World Economic Forum, 2018a). The most negative impacts will be felt on lower skilled labourers performing simple, repetitive and/or predictable tasks.

[8] Jobs are made up of a multitude of tasks, many of which are not easily automatable. While in some cases the core tasks can be fully mechanized, in other cases automation doesn't eliminate jobs but rather changes the nature of the tasks to be performed.

Box 4 on the coal and steel sectors respectively in the United States provides two examples of the impact that continued mechanization can have on the mining job market. The unskilled labour force is in many cases already fragile, as their unemployment rates are generally higher than average.

(ii) On the other hand, technological changes will also create new jobs, as people will still be required to operate and maintain equipment, to set up the parameters of autonomous routines, to create and revise the software to integrate the data coming from various sources.

Importantly, completely new opportunities will be created in areas thus far unknown. These are expected to be fewer in number, but targeted to highly skilled labour and in specialized areas. A number of new tasks will be piloted remotely, sometimes from headquarters in host countries, but also at times, elsewhere in the world.

Box 5 highlights an example from the automated underground mine in Kibali, DR Congo requiring a significantly smaller workforce to operate a fully automated mine.

BOX 5. KIBALI GOLD MINE IN DR CONGO

The Kibali mine in DR Congo consists of an open-cast and an underground mine. The underground mine was designed as an integrated mine, which required significant investments to improve productivity through automation and mechanization. It operates with a small skilled workforce, where remote operators function underground from safe air-conditioned cubicles, managing the loaders that descend close to 800 m below the surface (Moore, 2019).

The mining company has invested in the training of local people to take over new jobs in the mine. However, it only employs six people in its corporate office in Kibali. Most of the business is run from out-of-country offices, where real-time systems have largely replaced the need for in-country corporate jobs.

(iii) In between the two, we also expect significant changes for certain categories of occupations that will be "enhanced and modernized" to become more productive. Labour performing these tasks will have to be upskilled and retrained to adapt to more modern techniques of production;

(iv) Other types of occupations will be significantly restructured or redesigned: the nature of the tasks will be different. Labour performing these tasks will have to be retrained if their initial skills were adapted to the new tasks. The WEF estimates that by 2022 53 per cent of workers will have to be reskilled and upskilled to perform new jobs (WEF, 2018b).

Disruptive technologies such as automation will not only alter the number and types of jobs available. It will strengthen the comparative advantage of highly skilled workers, in particular those who combine cognitive skills such as problem solving, leadership, emotional intelligence and creativity. They will become pivotal to the organization.

(v) The working environment will evolve into a more agile workplace, with a rise in the number of non-permanent/ contractual workers, who will be faced with demands for more flexible work options, including to work remotely. For locals this means they will be directly competing with people in the capitals and beyond for jobs that used to be reserved for them.

(vi) There will be a capitalization effect, as an increasing number of technological firms supply the mining sector, leading for new prospects for employment in those firms to increase (Frey & Osborne, 2013).

(vii) Labour impact on Indigenous communities is expected to be more significant than the national average. In fact, these communities are more vulnerable to technological disruptions because they tend to be over-represented in lower-skilled jobs and under-represented in higher-skilled jobs compared to other nationals in the mining workforce.

In particular, they are mainly employed in occupations most at risk, such as trades, transport and equipment operation, many of which are set to become obsolete or to be operated from remote locations.

In Australia, 60 per cent of mining projects are found close to Indigenous communities. Employment rates of Indigenous people are therefore higher (Hatch, 2017). They represent 55 per cent of machine operators and drivers, 24 per cent of technicians and trade workers, but only 5 per cent of professionals (Holcombe & Kemp, 2018). Similar trends are observed in Canada (Natural Resources Canada, 2019). Box 6 highlights other complexities on the labour market in Australia.

BOX 6. AUTOMATION IN AUSTRALIA

In Australia, the new jobs market arising from automation across various economic sectors increases demand for highly qualified people, such as managers and professionals— as well as for lower-skilled people, particularly in the services sector (hairdressers, restaurant waiters etc.). But the biggest negative impact has been for the workers in the middle, such as truck drivers or bank analysts (The Senate Australia, 2018).

The country is witnessing the side effects of job polarization (Hajkowicz et al., 2016) in the form of unemployed graduates that have skills for jobs that no longer exist or are being significantly automated, and the rise of new on-demand services—ranging from cyclists delivering food to taking your clothes to the laundry—that were replacing those middle jobs.

Automation is also threatening to radically restructure the country geographically. Most opportunities for future high-skilled jobs are being concentrated in "points of gravity" predominantly found in urban areas, in particular in "hubs," while peripheral regions are being "decimated" (Australian Council of Trade Unions, 2018).

Indigenous communities are often the frontline suppliers of mining local procurement. The net impact is likely to be more significant than at an aggregate level.

The speed and depth of technological adoption will depend on how successful the negotiations are with Indigenous communities and First Nations, including in advanced economies like Canada and Australia. The granting or renewal of mining licences may be conditional on local economic benefits such as employment, calling for an incremental approach to project development.

(viii) Gender-related employment impacts: Overall, male workers are expected to be disproportionately affected by job losses, on account of their current larger share of employment in physical jobs related to trades, transport and equipment operation, which are all at greater risk from automation (Hanrahan & Evlin, 2017). Those performing manual and physical tasks are also at greater risk of being affected by the changing skills needed for digital transformation (Conference Board of Canada, 2018).

A large number of women are employed in support occupations (such as finance, business or administrative roles). While there will be displacement for some of these roles, they will be proportionately less impacted, at least in the short term. Some of the tasks performed by women could be absorbed in other economic sectors experiencing a slower pace of disruption due to new technologies.

On the positive side, new job opportunities, executed in operation centres, may provide more scope for women in mining. Such work venues may be less intimidating than the male-dominated rock face or mine site. As well, there may be opportunities for working mothers to take jobs at remote operations centres, where the job being replaced at a remote site would not have been feasible. However, as mining companies consolidate monitoring and management activities at single global locations, these may reduce the scope of employment in domestic operation centres.

5.2 THE CHANGING ROLES AND NATURE OF FIRMS

New technologies can reshuffle mining value chains, disrupting both existing business models and the traditional roles and relationships among mining companies, their customers, their suppliers and even competitors. Some changes may include:

(i) The operational structure of the mining industry itself will change: Many companies have already switched from owning capital equipment to leasing it. Others outsource parts of their operations to contract suppliers (e.g., Anglo Gold Ashanti at Obuasi in Ghana).

(ii) New types of operators, such as tech providers or automotive manufacturers, may become strategic investors in mining projects (EY, 2018).

BOX 7. MINERS OF THE FUTURE

In 2018, EY ranked "disruption" as the 8th most significant risk facing mining and metals in 2019–20 (EY, 2018). Among the various types of disruptions feared by mining companies, one of them is the change in the mining landscape, where technology companies may take increasing stakes to become direct and indirect investors and hence become dominant players. In fact, 31 per cent of the survey respondents thought that technology providers have the potential to disrupt the sector (EY, 2018).

Two factors are driving these investments:

(i) Vertical integration, to secure access of supply of minerals (such as cobalt and lithium), tech-using companies are adjusting their investment models into mining so they can guarantee supply for their production. Tesla is one case in point.

(ii) OEM tech innovation companies (the likes of Sandvik; AtlasCorp etc.) who have access to capital are investing massively in innovation and mining technologies. In the future, they may become licence owners, if they are to bear most of the upfront investments. Mining companies may become contract service providers. OEMs will perform leasing and maintenance of assets and employ people to operate them.

(iii) Universities, R&D centres of excellence, and technological hubs will play a more prominent role in providing innovation ideas, solutions and high-tech services to the value chain (Nedelkoska & Quintini, 2018).

(iv) Technological innovation will come from new fields, such as biochemistry; bio-engineering; computer science. These disciplines are outside the traditional core competence of the mining sector, implying a need to either bring new areas of expertise on board, form strategic partnerships, or purchase/license new technologies developed by others.

6.0 MOVING FORWARD: WHERE DO WE GO FROM HERE?

This report focuses for the most part on trends in technological innovation, and the expected impacts of those trends, in particular on the labour market. In closing, it considers the next line of questions: what to do about the challenges and opportunities presented by those trends and impacts?

While technological innovation may provide opportunities for wider economic development, the main concern is how prepared are companies, governments and communities to face the upcoming changes? As the study shows, changes will not be homogenous across countries. In particular, demographic trends and levels of development will drive the need for country-specific solutions.

In the short term, an immediate challenge for industry leaders and policy-makers alike is to be able to anticipate the net effect of disruptive technologies on their labour force so that they can manage the transition, knowing that the new jobs created may not necessarily be made available to those who would have lost their jobs in the process. If not well managed, this scenario will exacerbate job polarization and inequality.

Alternative solutions will have to be proposed to those workers who will lose out, and the labour force must be prepared to take up new opportunities.

Navigating that challenge is essential to maintaining social stability and ensuring continued support from local communities for mining activities. It will avoid creating or widening the trust deficit among government, industry and affected people. But more fundamentally, it is critical for peace and political stability.

This section explores five sets of policy options that governments and mining companies might consider in seeking to address the disruptive impacts of new technology:

(i) Increased focus on skills development

(ii) Increased focus on some types of local content

(iii) Rethinking community engagement

(iv) New arrangements between host governments and mining companies

(v) New technology as part of the new deal.

6.1 INCREASING FOCUS ON SKILLS DEVELOPMENT

The development and application of new technologies in the mining sector require different competencies in the labour market (OECD, 2019). Successful adaptation to a new working environment will depend on the learning evolution of the labour force, meaning the extent to which workers are able to acquire new skills and adapt their competencies to remain fit to perform more sophisticated tasks. This is still an uncertain and unknown variable in many countries.

To adapt to the coming changes, governments and mining industries will need to have a profound understanding of the gaps and future skills needs. Today, it is estimated that there is a limited pool of people who have the requisite skills, in fields such as data science, analytics, predictive modelling and mechatronics (EY, 2018). Training programs, curricula and institutions will have to be adapted to respond to those changes. Social protections programs will have to been revised to take care of the most vulnerable workers who might fall out of the system (World Bank, 2019).

The following conditions are required to address the knowledge and skills challenge:

1. Skills development programs and educational systems will require some adjustments to enable workers to embrace the technological shift:
   (a) The general education level, in particular in developing countries, will have to be significantly improved. In many cases, inadequate primary and secondary level schooling makes it impossible for workers to take vocational training aimed at preparing them for the mining jobs of the future.
   (b) Education systems and training institutions will require significant adaptation. They have to focus at an earlier stage on data and digital literacy, a core competency to be required for most jobs of the future. Additionally, they need to place much more emphasis on STEM subjects: science, technology, engineering and mathematics. Science should not be left to be a field "option" in school, but rather a competency in itself (Committee for Economic Development of Australia, 2015), which should start from early childhood. This is already the case in Australia, where STEM learning is integrated in basic literacy, in early childhood education, as a step to prepare the next generation with appropriate competencies (The Senate Australia, 2018). Firms in particular should be encouraged to take science subjects at school.
   (c) Higher education and training systems (including university, technical and vocational training schools) will have to deliver the foundational skills that will allow learners to embrace new technological opportunities and to keep a competitive edge over machines, since those skills are (still) the least automatable and replaceable (OECD, 2019). These skills include:
      - **Human skills** such as (i) critical thinking or proficiency to challenge normative ideas and find solutions and responses beyond what is conventional, (ii) emotional intelligence, (iii) analytical skills, (iv) cognitive skills (v) creativity, (vi) interpersonal and communication skills; (vii) collaboration.
      - **Digital skills**, as a rule, as a basic competency for all workers of the future. At a more advanced stage, these are skills needed to create and manage data and develop software, ensure digital security etc.
      - **Practical management skills** to design and manage projects and business processes.

In Canada, academic institutions are responding to the evolving needs of the mining sector by reviewing their curricular and research programs and by facilitating work placements to enable real-work exposure in a wide variety of dynamic operating conditions. Institutions have also established better partnerships with the mining sector. In the future, mining engineering schools may seek to become more interdisciplinary. One way would be to amend curricula to attract students from emerging disciplines, such as genomics, computer science, and nanotechnology (Conference Board of Canada, 2018).

(d) Academic training will have to be combined with cognitive skills, social science and creativity. Lifelong training programs will be crucial to constantly equip employees with new competencies. The most nimble or versatile workers ideally need to have a blend of those different skills, to be able to adapt to future markets and workplaces (World Economic Forum, 2018a). These workers are likely to be in higher demand, as the mining environment evolves and becomes more flexible and collaborative. People with a blend of scientific and foundational skills (dubbed STEAM skills—science, technology, engineering, *arts* and mathematics), are expected to advance into more senior roles. However, they are also likely to be more volatile or more mobile across industries, which implies employers will have to pay them higher wages to retain them (Boy, 2013).

2. Training programs need to successfully embrace the generation shift. The existing workforce must be educated to the new world of work through innovative training programs and methods and retraining/ reskilling tools, both critical for smoothing a transition toward new types of tasks (WEF, 2019).

   To achieve this, training programs must facilitate continuous and dynamic learning over the career life-cycle of employees, to ensure that people keep pace with technological progress and other factors of change. This is crucial for employees performing tasks most at risk of technological disruption.

   Programs must be adapted to different age groups. For example, "millennials"[9] (Heather, 2017) have a natural predisposition for technology, as they grew up in "connected societies," notably through social networks. This new generation of employees is easier to train, and skills strategies will have to adapt to their capabilities. Mid-career and close-to-end-of-careers employees will need particular tailor-made support, as some of them may take more time to adapt to new working environments and to new software and machines.

3. Lifelong training is key to continuously upskill workers and empower them to pursue other interests and careers. This is a clear opportunity for mid-career workers, who are experienced, and can therefore improve their productivity, by astutely combining new skills learned with their experiences. Today, unless provided by the industry, mid-career workers are not encouraged to take flexible training on their own, in part because this often has a financial cost, but also because it is not always possible to take paid leave to do so (International Labour Organization, 2018). In the future, as continuous learning becomes more important, industries and employees will have to find a way to address this challenge.

4. Nurturing innovation and new technology requires adapting skills and capabilities of staff to better work together, away from the traditional silo approach (separate teams responsible for different parts of the value chain). Collaboration—in particular among workers who have

[9] The term refers to people born between 1982 and 2002.

never worked together—will be key. Working ecosystems will be more interdependent and interdisciplinary.

5. Talent retention within the industry will be key to minimizing direct competition with other sectors. The sector is too often perceived to be less attractive to the younger generation. It will need to give attractive salary packages as well as tailored reward programs to retain talents.

6.2 INCREASING FOCUS ON SOME TYPES OF LOCAL CONTENT POLICIES

One way to address the potential challenges that emerge from rolling out new technologies in mines is to rethink how local content policies can create more value in the economy. There are at least three salient types of local content typically sought for by governments from mining companies. These are:

- Direct employment of locals
- Procurement of local goods and services
- Local processing of mined materials (beneficiation).

While the number of directly employed locals may be reduced significantly for repetitive and manual tasks, opportunities will be available for new tasks. Training local staff during the investment phase is a way to prepare the workforce to be ready for the new jobs.

For jobs that will become obsolete in the mining sector, encouraging talent mobility across various sectors of the economy, in particular those less at risk from rapid technological change (e.g., smaller companies; some service sector positions etc.), would be a way to redirect the workforce to fill jobs elsewhere.

To tackle the new labour market requirements in the mining sector, there is a clear role for the mining industry and government to work together to enhance digital skills in all school curricula through national education programs ranging from primary to tertiary education and technical schools. It is essential to equip current and future local workforces with the ability to compete for the high-skilled jobs of the future and the adaptability to be resilient to changing job descriptions in the future.

The roles and responsibilities of various players should be clearly outlined: at a minimum, mining companies need to outline their skills needs in advance and indicate clearly which ones may become obsolete, so that action may be taken to manage the transition. Educational institutions also have an important role to play in revising their curricula and including new disciplines in their teaching programs, which should start early in children's learning programs. Further, business and training institutions should step up efforts to include practical and on-the-job experience as a compulsory course requirement.

On procurement of local goods and services, there are a number of well-known strategies for boosting local procurement, from supplier development programs to unbundling contracts so locals can bid more easily. Procurement related to employment is likely to be the most affected as labour-replacing technologies are adopted.

To minimize negative impacts on local procurement, given the increasing role of tech-providing companies, new arrangements (such as joint ventures) will have to be defined to provide opportunities for local industries to participate in the supply chain. In India, for instance, local IT firms are partnering with digital service providers and mining companies in the deployment and monitoring of the digital platform (EY, 2017b)

An important challenge is to ensure that people from mining communities are able to benefit from those business opportunities. As with direct employment efforts, a focus on boosting local procurement involves chasing a bigger piece of a shrinking pie.

The history of policies to encourage downstream local processing of materials is replete with instructive failures, with few success stories. But where success is possible, increased local processing would be another way to replace the benefits formerly derived from mining-related employment of locals.

6.3 RETHINKING COMMUNITY ENGAGEMENT

An obvious way for mining companies to address the loss of local employment-related benefits is to focus on supporting community economic development in the affected communities. This is not a straightforward prospect and certainly requires to new approaches to community engagement, as development practitioners have discovered over decades of experience. No one should underestimate the challenges for mining companies, whose core expertise lies elsewhere, trying to plan and implement initiatives in this space.

A major set of challenges revolves around ensuring that any efforts are consistent with the priorities of the affected communities and that those are jointly agreed with the beneficiaries—not decided without their consent.

Support can come in financial terms: several mining companies already have "community development fund," and in many cases, these have not had very convincing long-term impacts. In order to work, these funds must be designed in a way that they can be used as "impact investments," with a clear goal of generating socioeconomic benefits, with a financial return so they can be self-sustaining over time. As a rule, it is harder to foster economic development through funded initiatives than through direct employment.

Beyond financial support, it is important to foster knowledge-sharing from tech providers to local firms, combined with capacity-building programs. Government may need to examine policy options for workers looking to redeploy their talents to other sectors or growth occupations. These programs and policies should facilitate increased Indigenous participation and Indigenous-led economic development in communities, which can also ensure proponents' continued ability to operate in and around communities.

Another specific form of community economic development involves the sharing of existing mining infrastructure (e.g., roads, rail, water treatment and supply, Internet access) or sharing new infrastructure triggered by innovation in processes with the affected communities. Mining companies in countries like Peru have shared the benefits of water-saving technologies, initially critical to mining operations in water-scarce areas, with local communities and economic sectors. In 2016, the Peruvian copper mine Cerro Verde build a water treatment plant to reduce water usage for its refinery operations in the water-stressed region of Arequipa. Water thus treated was also shared with local farmers (Connell, 2016). This has improved the living conditions through a much-needed support to local agricultural sector, which in turn managed to create more wealth and jobs in the region. Similar initiatives exist with the sharing of electricity resulting from off-grid innovation for power generation. Again, success is conditional to planned education support and training programs aimed at new technologies.

6.4 NEW ARRANGEMENTS BETWEEN HOST GOVERNMENTS AND MINING COMPANIES

If tangible benefits (such as employment, community investment, funding for social supports, etc.) for communities are set to diminish over time, there is a need to rethink and develop alternative programs and policies to ensure the benefits of mineral development are shared equitably.

These can include gradual changes to regulation, fiscal regimes and industry–public engagement. Failure to agree on a joint collaborative approach may lead to increasing difficulty to secure the necessary public support for future mine development. For instance, this may result in unilateral decisions by policy-makers to increase taxes or royalties levied on mining firms that employ fewer people. Such a decision would be based on the assumption that new technologies would bring significant and sustained profit streams as a result of more efficient operations and more productive mines, and therefore may be subject to higher taxes. This is, however, not a certainty, as upfront investments are very substantial for greenfield projects, and brownfield retrofits face declining ore grades, and improved productivity does not necessarily guarantee higher profits. In the longer run, rents get competed away, and new technologies may simply become a prerequisite to staying in business. A more nuanced version of tax reform might see tax rates somehow indexed to profitability (i.e., a resource rent tax).

Another possibility may be to rethink government ownership of mining resources. The aim of such strategies would be to derive more national benefits from the resource. Several options are available, including increased state-controlled shares, like the one between DeBeers and the Government of Botswana (IGF, 2018) or by entering into contract arrangements along the lines of production-sharing agreements that exist in the oil sector. However, lessons must be learned from the failures of past state-owned initiatives as these may lead to risks of corruption and bad governance as a result of patronage and rent-seeking that may arise from bids to control financial resources. Success would depend on mines being competitive in global markets (so that the state does not end up subsidizing operations) as well as on the existence of well-governed transparent and accountable institutions.

Governments may also seek to promote national champions (Cosbey & Mann, 2014; UNECA, 2014). Those can be privately owned large companies or state-owned companies. Best practices would be instructive, such as in Codelco in Chile and Office Cherifien des Phosphates in Morocco.

As with community economic development funds, a critical condition would be to ensure that increased funds to the government—in this case, in terms of a stream of profits or dividends—are effectively translated into tangible benefits at the level of the affected communities.

Another potential advantage of those new forms of arrangements is that parties may be more willing to use local content in their operations, in ways that increase local benefits. Again, it should not be done at the expense of the competitiveness of the industry.

6.5 NEW TECHNOLOGY AS PART OF THE NEW DEAL

New technologies have impacts far wider than reduction in labour force. It is possible that some of the beneficial impacts of new technologies could help to offset or compensate other negative impacts from reduced local employment and procurement.

If shared or put to the benefit of local communities, technological infrastructure—e.g., IT, energy- and water-saving technologies—can potentially provide gains that minimize the negative impacts in the medium to long term, unlocking economic opportunities that would not have otherwise been possible.

Access to energy through the sharing of mines' energy generation or access to water (resulting from the industry's efforts to minimize the use of fresh water), can provide scope for non-mining industrial activities, which can in turn provide significant economic benefits.

In South Africa, Anglo American has developed a pathway to minimize (or eliminate when possible) the use of fresh water from its mining processes. The company has committed to reducing the use of fresh water in water-scarce regions by 20 per cent[10] and increasing its water recycling levels to 75 per cent by 2020 (Leonida, 2019). Water savings thus generated had helped to ease tensions over access to water that emerged in 2016 in Limpopo province between agriculture and the mining sector.

The fully connected mine operation generates a great deal of data, and if shared some of that may create benefits for local populations. Local communities, for example, might benefit greatly from real-time data on tailings dam stability or effluent water quality. Similarly, host governments might benefit from access to operational data that would help them track quantities and qualities of final product; one of the challenges in addressing base erosion and profit shifting is precisely accurately verifying that data.

In closing, it is worth underlining that none of the policy options surveyed above is likely to be a perfect solution. *Some* may address *some* challenges in *some* contexts. Further exploring their various strengths and weaknesses will help policy-makers, mining companies and affected communities better understand the options on the table and be better prepared for the coming changes in the mining sector.

[10] The aim is to reduce its abstraction of fresh water in water-scarce regions by 50 per cent by 2030.

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