DIGITALIZING EXTRACTIVE INDUSTRIES: STATE-OF-THE-ART TO ART-OF-THE-POSSIBLE OPPORTUNITIES AND CHALLENGES FOR CANADA

Ray Gosine and Peter Warrian

Table of Contents

Please cite this document as:

About the Authors

Dr. Ray Gosine is a Visiting Professor at the Munk School of Global Affairs, University of Toronto, and a Professor of Engineering, Memorial University of Newfoundland. He has held various senior roles at Memorial University, including Vice-President Research (pro tempore), Dean of Engineering, and the J.I. Clark/C-CORE Chair of Intelligent Systems for Operations in Harsh Environments. He also held an NSERC Chair in Industrial Automation at the University of British Columbia. Dr. Gosine is a Fellow of the Canadian Academy of Engineering (FCAE) and a Fellow of Engineers Canada (FEC).

Dr. Gosine's research is in the areas of intelligent systems, robotics, and automation with a particular interest in the applications of these technologies to natural resource industries. He is interested in the broader implications of advanced technologies, and he recently chaired a Public Review Panel (www.nlhfrp.ca) that considered the scientific, technical, socio-economic, public policy, regulatory, environmental, and public health issues associated with unconventional oil and gas development (i.e., fracking).

Dr. Peter Warrian is a Senior Research Fellow at the Munk School of Global Affairs, University of Toronto. He is Canada's leading academic expert on the steel industry, and he was formerly the Research Director of the United Steelworkers of America and the Chief Economist of the Province of Ontario.

Dr. Warrian's current research is on knowledge networks, supply chains, and digital manufacturing. As a member of the Innovation Systems Research Network (ISRN), funded by the Social Sciences and Humanities Research Council of Canada (SSHRC), he has worked on the interface between the steel industry and the auto industry, particularly in the area of lightweight materials and the interaction of software and advanced materials.

Glossary
(Adapted from Wikipedia and the Gartner IT Glossary)

Analytics: the discovery, interpretation, and communication of meaningful patterns in data

Automation: the use of computer-controlled systems to operate equipment with minimal or reduced human intervention

Automation Anxiety: fear about the impacts of automation on peoples' work and daily life, including fear about the safety of automation technology and its capacity to replace human labour and expertise

Big Data: large and/or complex data sets that cannot be processed using traditional data processing software

Artificial Intelligence (AI): intelligence exhibited by machines to mimic the cognitive functions that humans associate with other human minds, such as learning and problem-solving

Autonomous Vehicles: a vehicle that can drive itself using various digital technologies for route planning, navigation, environmental sensing, and obstacle avoidance

DARPA: Defense Advanced Projects Research Agency in the United States

Digital Technology: computerized devices, systems, and processes

Digitalization: ongoing adoption of digital technologies across society

Disruptive Technology: technology typically produced by outsiders and entrepreneurs rather than market-leading companies that creates a new market and value network and eventually disrupts an existing market and value network, displacing established market leading firms, products, and alliances

E&P: exploration and production within the oil and gas industry

Geomatic Survey: using instrumentation to gather geographic or spatially referenced information

Gross Domestic Product (GDP): the total value of all goods and services produced within a country or a region, which gives an indication of the size of an economy

Human-computer Interaction: the interface between people (users) and computers

Human-robot Interaction: the interface between people (users) and robots

Industry 4.0: the current trend of automation and digitalization across industries

Innovation: the application of better solutions to meet new requirements, unarticulated needs, or existing market needs through more-effective products, processes, services, technologies, or business models

Intelligent Systems: a physical system that incorporates artificial intelligence into its function

Internet of Things (IoT): the network of physical devices, vehicles, and other items embedded with electronics, software, sensors, and actuators that enable these objects to collect and exchange data

LHD: Load-Haul-Dump mining vehicle that is similar to a front-end loader

Metocean: the combination of wind, wave, and climate conditions

Mobile Computing: human–computer interaction using a computer transported during normal usage

NSERC: Natural Sciences and Engineering Research Council which funds academic research in Canada

Peak Oil Demand: corresponds to the time when the global demand for oil reaches its maximum level, after which demand decreases

Production: the process of extracting minerals and oil and gas resources

R&D: Research and Development

Remotely Operated Vehicle (ROV): a tethered underwater mobile device that is unoccupied, highly maneuverable, and operated by a crew aboard a vessel

Robots: computer-programmable machines that can take the place, partially or fully, of humans to carry out a complex series of actions automatically

Seismic Survey: generating sound waves and measuring their reflections from within the surface of the earth in order to build up an image of the subsurface

Small and Medium-sized Enterprise (SME): in Canada a small or medium-sized enterprise is a business that has less than 500 employees, with 98% of SMEs having fewer than 100 employees

Supply Chain: system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer

Tele-operation: operation of a system or machine, typically a robot, at a distance

Transportation-as-a-Service (TaaS): describes a shift away from personally owned modes of transportation and towards mobility solutions that are consumed as a service - also known as Mobility-as-a-Service (MaaS)

Upstream Oil and Gas Industry: companies that search for potential underground or underwater crude oil and natural gas fields, drill exploratory wells, and subsequently drill and operate the wells that recover and bring the crude oil or raw natural gas to the surface

Value Chain: set of activities that a firm operating in a specific industry performs in order to deliver a valuable product or service for the market

Wearable Technology: digital technology worn by a human in order to carry out a particular function, such as to collect data or provide sensory augmentation

Executive Summary

Industries based on extractive resources, primarily minerals and oil and gas resources, are important to the Canadian economy in terms of their contributions to employment, gross domestic product (GDP), capital expenditure, construction-related investment, revenues to governments, export value, and investment in Canadian companies. Extractives industries are truly pan-Canadian and important from both a national perspective and a regional perspective, especially for resource regions. The companies are multinational in scope, with global workforces, supply chains, and consumers of their commodities.

As more accessible resources are fully exploited, there are technical and scientific challenges to be overcome to dig deeper or extract lower grade minerals and to drill in more remote or challenging areas to produce oil and gas. There are also challenges arising from the complexity of the underlying economics of extractive industries, which are exacerbated by protracted commodity price variability, interspersed with occasional and surprising price shocks. These difficult economics are further compounded by the increasing challenges resulting from satisfying the perceived and real entitlements of various stakeholders. There is a requirement to achieve and maintain win-win-win relationships among communities, governments, and industry stakeholders, all of which are `invested' in resource development projects and have increased expectations with respect to returns.

Extractive industries, like many other sectors of the economy, will be significantly impacted by disruptive digital technologies, variously referred to as digitalization, Industry 4.0, and the Fourth Industrial Revolution. These technologies include advanced robotics, big data and analytics, artificial intelligence, mobile computing, wearable technology, internet of things (IoT), and autonomous and near-autonomous vehicles. While there is widespread belief that digitalization will transform extractive industries, the timelines and consequences for such a transformation are less clear.

Looking forward, extractive industries operating in Canada must address challenges by developing, adopting, integrating, and applying recent and emerging digital technologies. It is only through innovation that the challenges experienced by extractive industries in recent years, and which are expected to persist or worsen into the future, can be addressed successfully. In addition to helping to address challenges, an embrace of digital technology could lead to new and currently unknown opportunities.

For both mining and oil and gas companies, the future could include heavily digitalized assets (i.e., oil rigs, mining equipment), capable of high levels of autonomy and inter-asset cooperation, operating within challenging natural environments (e.g., a deep or remote mine or far offshore oil field) monitored using advanced embedded and remote intelligent sensor technology. These digitalized assets and intelligent sensor technologies could be connected via innovative communication systems to digital enterprises (i.e., mission control centres and other remote centres of excellence), where experts would monitor production operations remotely, interact via technology with a limited number of field workers at production sites, and perform computational analysis on data collected from remote operations to optimize production, equipment maintenance, and asset utilization, while simultaneously ensuring regulatory compliance.   The digital enterprise could be part of a digital world in which technology would be deployed to improve supply chain management and resource management, to balance supply and demand for product, to manage contracting among project partners, and to help secure and maintain public confidence.

Globally, digital technology will transform extractive industries. For Canada, this provides an opportunity to lead in developing and commercializing the enabling technologies, in integrating these technologies into global operations, and in considering the broader socio-economic and regulatory consequences of digitalization of these extractive industries.

Digitalization of extractive industries in Canada will pose opportunities and challenges for a diverse range of stakeholders. In addition to the operating and supply and service companies, individuals and communities will be affected by digitalization, as will governments and institutions (e.g., education systems, regional development organizations, unions, and regulators). Successfully addressing the opportunities and challenges will require early and effective engagement of all stakeholders that is informed by realistic digitalization scenarios, timeframes for their implementation, and assessment of the broader issues and impacts.

(1.0) Brief Introduction to Digitalization

Disruptive digital technologies, including advanced robotics, artificial intelligence, mobile computing, internet of things (IoT), and autonomous and near-autonomous vehicles, were assessed to be among the top 12 emerging technologies that are expected to transform peoples' lives and the nature of work (Manyika, Chui, Bughin, Dobbs, Bisson, & Marrs, 2013). Variously referred to as digitalization, Industry 4.0, and the Fourth Industrial Revolution, such technologies will likely be ubiquitous, with applications across industrial and consumer markets (BDC, 2017).

As digitalization is advanced and applied across industries, the development of these digital technologies will, by necessity, include diverse players, many of which have not traditionally been part of the supply chain for large industry. The competitive advantage of firms "might erode or be enhanced a decade from now by emerging technologies— how technologies might bring them new customers or force them to defend their existing bases or inspire them to invent new strategies" (Manyika, Chui, Bughin, Dobbs, Bisson, & Marrs, 2013). This is true for Canada's natural resource industries, in particular `extractive' industries based on mineral and oil and gas resources.

(2.0) Canada's Extractive Industries and Digitalization

Canada's natural resource industries are important to the Canadian economy in terms of their contributions to employment, gross domestic product (GDP), capital expenditure, construction-related investment, revenues to governments, export value, and investment in Canadian companies (NRCan, 2017a). Furthermore, they help Canada contribute toward meeting the projected global demand for energy. On an annual basis, the economic impacts of natural resource industries include approximately 1.75 million direct and indirect jobs (~11% of national employment), 16% of GDP, 38% of non-residential capital investment, $25 billion in government revenues, $201 billion in

export value, and $582 billion in publicly traded company value. The majority of these contributions are associated with development of mineral and oil and gas resources.

According to Statistics Canada, "mining, quarrying, and oil and gas extraction" are among the top contributors to Canada's GDP, with a combined annual contribution of approximately $150 billion and almost 25% growth in the 12 months prior to May 2017 (Statistics Canada, 2017a). In 2016, there were approximately 260,000 people directly employed in these extractive industries (Statistics Canada, 2017b). There is mineral production in all provinces and territories of Canada, with Ontario, Quebec, and British Columbia leading in terms of production value, followed by Saskatchewan, Alberta, and Newfoundland and Labrador (NRCan, 2017b). There is oil and gas production in seven Canadian provinces, including Newfoundland and Labrador, Nova Scotia, New Brunswick, Manitoba, Saskatchewan, Alberta, and British Columbia, with prospects for resources in Northern Canada, Quebec, and Prince Edward Island (CAPP, 2017a). These industries are truly pan-Canadian and important from both a national perspective and a regional perspective, especially for resource regions. The companies, however, are multinational in scope, with global workforces, supply chains, and consumers of their commodities.

While it is important to recognize the significance of extractive industries to all regions of Canada, it is equally important to appreciate that the future of these industries entails considerable uncertainty. As more accessible resources are fully exploited, there are technical and scientific challenges to be overcome to dig deeper or extract lower grade minerals and to drill in more remote or challenging areas to produce oil and gas. There are also challenges arising from the complexity of the underlying economics of extractive industries, which are exacerbated by protracted commodity price variability, interspersed with occasional and surprising price shocks. These difficult economics are further compounded by the increasing challenges resulting from satisfying the perceived and real entitlements of various stakeholders.   There is a requirement to achieve and

maintain win-win-win relationships among communities, governments, and industry stakeholders, all of which are `invested' in resource development projects and have increased expectations with respect to returns.

In general, mining and oil and gas companies have adopted a conservative approach to investing in research and development (R&D) in Canada compared with other industrial sectors (ResearchInfosource, 2017a). By way of illustration, with the exception of Canadian Natural Resources Limited, there were no oil and gas or mining companies in the top 15 corporate R&D spenders in Canada in 2016. In addition, for all oil and gas and mining companies, the R&D expenditures as a percentage of total revenues were among the lowest of any industries. In many cases, their R&D expenditures were lower by a factor of 10 or more. It is important to appreciate that weak R&D investment by extractive industries in Canada predates the current depression in commodity prices. In fact, the position of extractive industries among Canada's corporate R&D spenders remains similar to their position in 2010 (ResearchInfosource, 2010).

There is also considerable discussion about the appetite for mining and oil and gas companies to adopt new technologies. Canada's mining industry was once thought to be a world leader in terms of embracing new technology.   For instance, a 2001 report prepared for the Mining Association of Canada noted "the Canadian mining industry has undergone a profound transformation to a high-tech industry and is now one of the world's most dynamic and technologically advanced. With its strong links to other high technology industries both as a user of their technologies and as a supplier of inputs, it is a driving force in Canada's new knowledge-based economy" (Global Economics, 2001). Fast forward to 2017 when Barrick's Chief Innovation Officer, reflecting on the role of digital technology in the mining industry, stated "the mining industry is the least digitized industry in the world. It is also an industry that has been slow to adopt change and innovation" (Barrick, 2017). A recent review of the start-of-the-art of robotic mining technology also noted that "the resource industry has a conservative history and

the implementation of new technologies and processes must often overcome significant resistance to change" (Marshall, Bonchis, Nebot, & Scheding, 2016). This resistance is thought to result from "skepticism about technology and fear of losing one's job".

Some analysts believe the slow pace of technology adoption is not due to a lack of receptivity to new technology, since there are examples of `digital mining' dating back to the 1950s. Rather, practical issues challenge mining companies, including the perception of a high cost of implementation, poorly-defined business cases, and a lack of digital education and understanding (EY, 2017a). Others, however, feel the mining industry is simply content to utilize the same technology and processes that are standard across the sector (Koven, 2014). Preliminary work to compare the adoption of digital technology in Canada's agriculture and potash/uranium mining industries suggested agriculture follows standard adoption theory when it comes to digital technology, while that is not the case for the potash/uranium mining (Phillips & Wixted, 2017).

As discussed by Steen et al, the nature of innovation in the mining sector may be "different from other industries" and would not be "well captured by traditional innovation measures such as R&D expenditure and patents" (Steen, Macaulay, Kunz, & Jackson, 2017). Innovation tends to occur in the supply chains, and understanding the relationships between mining companies and the supply chains is important for understanding how innovation occurs in the mining sector.

Concerns have also been expressed with respect to the adoption of new technologies by the oil and gas industry. In particular, it was suggested the "speed of adoption lags behind other industries that are subject to the same rash of safety, legal, commercial and financial pressures faced by energy companies" (LR, 2015a). Others, however, see the current low-price oil environment as providing the impetus for oil and gas

companies that have been slow to adopt the latest innovations to embrace innovative technology-based solutions (Constas, 2017).

There are heightened expectations related to the health, safety, and environment (HSE) performance of extractive industries and to the achievement of shared-values among extractive industries and the communities and regions where these resources are exploited. By their nature, extractive industries modify the environment in which they operate, often impacting the environment negatively. With growing political and public awareness about anthropogenic climate change and the need, from countries to individuals, to counter the effects of climate change, extractive industries are challenged to minimize the negative environmental impacts from their operations.

Increased concern about risks to public health and worker safety from the processes used by extractive industries have further raised the stakes for mining and oil and gas companies. Addressing public concern about the impacts on the environment, public health, and worker safety will be a prerequisite for securing the public confidence required to initiate future resource development projects, to increase productivity and the efficiency of existing operations, and to be competitive and well-positioned to export Canadian commodities into volatile world markets. Moreover, this cannot be achieved by a `business-as-usual' approach. For example, cost-cutting as a tactic for achieving productivity improvement is thought to have reached a point of diminishing returns for the oil and gas industry (Farah, 2016).   As proposed by E&Y, "the present low oil price is disruptive by nature and calls for more than just rapid reduction of cost through downsizing or budget cuts across the organization" (EY, 2015b).

Extractive industries operating in Canada must `disrupt' the way they do business. This could include the development, integration, and creative wide-spread application of recent and emerging disruptive technology, particularly digital technology. It is only through innovation that the challenges experienced by extractive industries in recent

years, and which are expected to persist or worsen into the future, can be addressed successfully.

In addition to helping address challenges, an embrace of digital technology could lead to new and currently unknown opportunities. A digital transformation could give rise to potential benefits of capitalizing on new revenue opportunities, lowering costs, and improving efficiency (Geissbauer, Vedso, & Schrauf, 2016). Digital technology may also help extractive industries meet corporate social responsibility expectations (Roscoe, 2015). For example, digital technology may enable improved traceability of the social and environmental impacts of global supply chains for extractive industries. Furthermore, use of digital technology could help increase transparency and improve communications among diverse stakeholders.

Communities, companies, and governments that have traditionally benefitted (e.g., employment, royalties, taxes, revenues, and profits) from Canada's extractive resources need to understand how disruptive technologies could affect the future benefits that may be derived from exploiting these resources. The question about who is benefitting from resource extraction projects is an emerging issue for resource development, with concern about decoupling value creation from the site of production. For example, in the case of employment benefits in mining regions, the introduction of remote operations centres, depending on their locations, could lead to an urbanization of the mining workforce, with a reduction in rural employment opportunities (McNab, Onate, Brereton, Horberry, Lynas, & Franks, 2013). It is also important to understand and acknowledge that digitalization has the potential to facilitate a greater decoupling of value creation from the site of production and, as a result, further change the nature and distribution of benefits.

Canada's extractive resources are exploited by multinational corporations that require a competitive advantage to operate in Canada. Any competitive advantage arising from

digitalization that may benefit Canada will depend on a number of critical factors, including a corporate culture that supports innovation; effective and efficient regulation that can accommodate technological change; access to highly qualified people who can support a digitalized industry; and innovative win-win-win relationships among communities, governments, and industry. Technology alone will not provide the competitive advantage that will keep these industries operating in Canada.

(3.0) Mining Context

Canada's mining industry "supplies the raw materials needed to produce many of the consumer goods we rely on in our daily lives, as well as those of the future, from utensils and hand tools to smartphones and electric cars" (NRCan, 2017b). The Mining Association of Canada reported the Canadian mining industry provided over 550,000 direct and indirect jobs, contributed $56 billion towards GDP, and accounted for 19% of the value of goods exported from Canada (MAC, 2016).

Over the past 10 years, China emerged as the single largest consumer of many base metals (Armbrecht, 2015). These base metals are essential for global industrial production and construction, with commodity prices serving as an important indicator of global economic changes (Matsumoto, 2015). The prices for iron ore and base metals, including copper and nickel, generally declined between 2011-2016, but showed some modest increases in 2017 (InfoMine, 2017). Concerns about whether there would be sustained demand for base metals by China, coupled with increases in supplies from developing countries, are thought to be behind the decline in base metal prices after 2011 (Matsumoto, 2015). Copper, however, rallied at the end of 2016 based on an increase in imports by China and, following the U.S. election, based on the mistaken belief that the President-elect's $500 billion infrastructure plan would significantly increase demand (Jamasmie, 2017).   While prices for precious metals, such as gold, are subject to different forces than those influencing base metal prices, gold prices have declined significantly since 2011 (InfoMine, 2017).

In 2016, Canada's primary mineral products by production value included gold, copper, potash, iron ore, coal, and nickel, representing 60% of the total minerals production value. Commodity prices and production volumes, however, can change rapidly, as illustrated by significant changes in production values between 2015 and 2016 for Canada's primary mineral products.   For metal production, iron ore and gold production values increased by over 30% and almost 9%, respectively. Nickel production value was down approximately 16%, while copper production value was down by just over 9%. Metal production volumes were comparable between 2015 and 2016. The production volume of potash declined by just over 11%, while the production value decreased by almost 37%. Canada also aspires to be a major producer of rare earth elements that are increasingly important for manufacturing components and devices, such as wind turbines, hybrid and electric vehicles, batteries, medical imaging equipment, speciality glass, lasers, and computers (NRCan, 2016).

In general, mineral prices are based on a complex set of factors, including geopolitics, speculative investment, and supply and demand, in particular the evolving demands of emerging economies. As a consequence, prices are prone to shocks and cycles resulting in long-term uncertainty within the global mining industry.   The downturn in mineral prices between 2011-2016 forced the mining industry to drive down costs to the point where further cost-cutting would result in diminishing returns (Deloitte, 2017). Embracing new technologies, many of which would be found beyond the mining industry, could enable significant productivity gains by mining companies in the future.

As noted by McKinsey, lower grade ores and longer haul distances have contributed to decreasing productivity levels across worldwide mining operations, with a drop by as much as 28% over 10 years (Durrant-Whyte, Geraghty, Pujol, & Sellschop, 2015). Other factors contributing to the decline in productivity include a decrease in labour productivity due to inexperienced teams, high turnover, an aging workforce, and a focus

on volume rather than efficiency; a decrease in capital productivity due to poor equipment utilization and a lack of innovative technology; and a failure to capitalize on economies of scale as mines expanded, leading to increased overhead costs and management inefficiencies (EY, 2017b). In general, there has been little incentive to invest in innovation initiatives during periods of high commodity prices and little capacity to do so during times of low prices.

For some minerals, extraction depends on being able to mine efficiently and safely at great depth. Some of the deepest mines in the world are gold mines in South Africa at depths of approximately 4 kilometres (World Atlas, 2017).   Canada's deepest mines are the Kidd Creek copper/zinc mine in Timmins, Ontario at a depth of almost 3 kilometres, and the Creighton nickel mine in Sudbury, Ontario at a depth of approximately 2.6 kilometres.   Deep mining exacerbates the efficiency and safety challenges for underground mining.   In the case of deep mining in Sudbury, at depths below 2.5 kilometres there are challenges from heat and rock stress conditions that can negatively impact on the safety and stability of the underground environment, requiring increased ventilation and other infrastructure to support people and equipment (Vella H. , 2017).

The move toward sources of renewable energy raises the prospect for seabed mining to meet the demand for minerals required to manufacture renewable energy systems. For example, high efficiency solar panels are manufactured using tellurium (DOE, 2016) (Shukman, 2017). One tellurium deposit near the Canary Islands is thought to represent one-twelfth of the world's supply at concentrations vastly higher than land-based deposits. The International Seabed Authority, of which Canada is a member state, is developing a Mining Code to support the regulation of marine minerals prospecting, exploration, and exploitation in seabed areas outside of national jurisdiction (ISA, 2017). Development and application of automation technologies feature prominently in a Norwegian pilot programme on deep sea mining, particularly in relation to mineral

exploration and extraction (NTNU, 2017). Automation could help minimize the negative environmental impacts of such industrial activity.

(3.1) Digitalization in Mining

It has been proposed that digitalization would enable a breakthrough in improving productivity, safety, and environmental performance for the mining industry (Arnoldi, 2017). In its prediction of the top trends for 2017 for the mining industry, Deloitte rated the digital revolution among the top issues with the potential to transform the industry (Deloitte, 2017). While the mining industry has adopted advanced mine planning and modeling software tools to optimize mine designs and production operations, these tools tend to generate designs that are based on a standard suite of mine designs or that use existing operating equipment and methods.

For many years, underground miners have been working with tele-operated drilling and loading machines (Cosbey, Mann, Maennling, Toledano, Geipel, & Brauch, 2016). Early advances included tele-operated Load-Haul-Dump (LHD) vehicles that utilized line-of-sight remote operation. The operator stood at a safe distance from the LHD as it was being loaded under unsupported ground. In this application, the operator used a chest-mounted console to guide the LHD through the loading process and in backing away from the ore pile. The operator would then get back on the LHD and manually drive the vehicle to its unloading point, unload the vehicle, and return to the loading point where the tele-operated loading process was repeated (Caterpillar, 2017). Marshall et al provided an overview of modern mining practice and a state-of-the-art review of mining robotics for both surface and underground mining operations (Marshall, Bonchis, Nebot, & Scheding, 2016).

In late 1990s and early 2000s, Canadian industry and academia were leaders in R&D related to tele-operated mining with the support of PRECARN, an industry consortium designed to translate advanced research in robotics and intelligent systems into

practical use (The Scientist, 1987).   In 1998, Canadian nickel mining company Inco articulated a vision for automated mining whereby "from any location in the world, a tele-operator can instruct intelligent, automated mining equipment to execute their missions. If the equipment encounters an unexpected situation beyond its ability to manage, it will ask for help. The tele-operator will respond immediately to requests for help from a wide range of intelligent, automated mining equipment" (Inco, 1998).

With the support of PRECARN, Inco along with technology providers and academic partners pursued a series of technology development projects to automate various types of mining vehicles and operations in order to improve productivity (Werniuk, 2001). In 2007, Orica Ltd., in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) from Australia and C-CORE from Canada, demonstrated tele-operation of an explosive emulsion loader (C-CORE, 2007). Due to the technology limitations of the time, these projects generally focused on single-point, rather than system-wide, solutions. Today's technology can support more radical innovation, targeting the entire value chain and providing the greatest prospect for transformation in productivity.   PRECARN was also instrumental in supporting industry-university collaboration related to human-machine interaction for heavy equipment, leading to the spin-off of Motion Metrics International from the University of British Columbia in 2000 (ICICS, 2010). Today, Motion Metrics International continues to develop machine vision and sensor systems directed toward improving "safety, efficiency, and productivity in mining" (MMI, 2017).

During this period, there were also research chairs at Canadian universities focused on mining automation, including the NSERC/Noranda Chair in Mining Automation at Ecole Polytechnique de Montreal and a Canada Research Chair (CRC) in Robotics and Mine Automation at Laurentian University.   Penguin ASI, a technology company based near Sudbury, Ontario and developing automation technologies, is a spin-off from the work of the CRC at Laurentian (Mining Global, 2014).

Other recent advances have been demonstrated for underground mine operations, including locating miners on the surface, or away from the mine site, and out of danger, with advanced human-machine interface tools for remote supervision and control of multiple highly-automated mining robots having auto-pilot and navigation capability. The current state-of-the-art involves automation of discrete phases of the mining cycle rather full automation of the mine site (Watkins, 2017).

In September 2016, Barrick and Cisco announced an ambitious partnership to integrate digital technology across all of its mine operations at Cortez, Nevada (Barrick, 2016). Mining and construction equipment manufacturer Altas Copco offers tele-operated and autonomous vehicles, with the primary drivers for automation being safety, productivity, qualified labor, and production costs (Atlas Copco, 2015). Sandvik, another manufacturer of automated LHDs, reported a 30% improvement in haulage productivity through use of their systems (Sandvik, 2017). There have been reports of considerable advances in the development and application of autonomous trucks for surface mining applications at BHP Billiton and Rio Tinto mines, and at Suncor oil sands operations (Simonite, 2016) (Gershgom, 2016) (Topf, 2016).

In the future, many direct production jobs in mining could be carried out from operation centres distant from production sites. Such operations could be safer because of reduced exposure of workers to dangerous and inhospitable environments, with increased productivity, lower environmental impact, reduced energy requirements, and lower capital and operating costs. For example, while locating equipment operators at a distance from production sites may decrease productivity by removing some of the cues (i.e., visual, audible, tactile and olfactory) they have at the rock face, there are efficiency gains from significantly decreased transit times to the production sites.

Overall, disruptive technologies, such as the internet of things (IoT), big data and analytics, automated vehicle technology, robotics, advanced imaging and sensing systems, wearable computing, and other intelligent systems technology, could become commonplace within the mining industry. Their widespread application would facilitate greater connectivity and autonomy of assets, with increased amounts of data collected and processed in real-time to aid in planning, optimization, and execution of operations. These technologies could help manage and coordinate various manually-operated, remotely-controlled, semi-automated, and automated vehicles and machinery working simultaneously at a production site.

While the benefits of emerging digital technologies may be realized by the mining industry, this would require companies to embrace Industry 4.0, a choice that "could be the most important strategic decision that companies make" (Yeates, 2017). Currently, fewer than 10% of mining companies are thought to have developed a digital strategy.

(4.0) Oil and Gas Context

Canada's oil and gas industry is the fifth largest producer of oil and gas in the world, with significant resources exported to international markets (NRCan, 2017c). Canada ranks third in terms of largest crude oil reserves. The contribution of oil and gas to Canada's GDP was estimated to be 7.5%, or around $135 billion annually (Ivey, 2016). The Canadian Association of Petroleum Producers (CAPP) estimated the direct and indirect employment in Canada's oil and gas industry was approximately 425,000 people (CAPP, 2017b). Furthermore, every province in Canada benefitted from the direct and indirect jobs created by the oil and gas industry, with Ontario, a province currently without oil and gas production, experiencing 12% of the employment impact (CERI, 2017).   There is concern the recent loss of talent from the oil and gas industry to other industries as a result of the downturn in oil prices will make it difficult to attract qualified employees when the oil and gas industry rebounds.   The contributions by oil

and gas workers to GDP significantly exceeds the national average of GDP contributions from workers in other industries (Ivey, 2016).

As with projections of demand for mineral resources, there is also considerable uncertainty and debate regarding the long-term demand for petroleum resources. Currently, gasoline consumption for automobiles counts for almost 50% of petroleum consumption (EIA, 2017).   Disruptive technologies and changes in driver habits, such as improved electric vehicles (EVs) capable of greater distances, autonomous vehicles, and Transportation-as-a-Service models of personal transportation, could lead to a reduction in fuel consumption by owners of light vehicles, as could decisions by governments to ban or limit the number of vehicles using internal combustion engines.

The United Kingdom and France recently announced bans on the sale of new vehicles with internal combustion engines (ICEs), effective 2040 (UK, 2017) (Chrisafis & Vaughan , 2017). Volvo also announced that, effective 2019, all of its new vehicles would be hybrid or electric vehicles (Marshall A. , 2017b).   It has been proposed, however, that there may be insufficient differentiation between the performance of electric vehicles and conventional ICE-based vehicles to cause consumers to move away from ICE-based vehicles in significant numbers (Tertzakian P. , 2017a). The decisions by some countries to announce bans, therefore, are attempts to override market forces. This is not to minimize the immediate impact of EVs on the oil and gas industry. The bans and plans of companies like Volvo are thought to be impacting the "psychology of investors who finance oil assets, services and infrastructure" such that "the result of all this next-decade confusion is that less money is going to be flowing into the oil business" (Tertzakian P. , 2017b).

While oil companies have started to discuss the notion of 'peak oil demand', there is disagreement among major oil companies with respect to when this will occur. It is important to note that the recent discussions around peak oil demand are in contrast to

previous references to `peak oil', which referred to the time when maximum oil production would be reached, after which production would decline despite continuing strong demand (Rapier, 2017). Earlier peak oil concerns predated the surge in the development of unconventional oil resources in the U.S. using hydraulic fracturing technology and the push toward alternative sources of fuel. The Wall Street Journal recently reported Statoil and Shell are projecting peak oil demand will occur by 2025-2030, while Exxon and Chevron do not believe peak oil demand is in sight (Cook & Cherney, 2017).

In its 2017 Outlook for Energy, ExxonMobil projected a 25% increase in the global demand for energy over the next 23 years, driven by an increase in population and in the standard of living in developing countries (ExxonMobil, 2017). This growth would be predominantly from India and China, and it would also be driven by a 50% increase in the energy demand from commercial transportation and by natural gas replacing coal as a fuel source. BP projected a similar increase in global energy demand, with an increase by 30% over the next 20 years, primarily from rising prosperity in emerging economies (BP, 2017). In the BP forecast, the demand for oil would continue to grow, but at a slower pace than recently experienced and with demand growth driven by non-combusted use of oil. BP also projected reductions in fuel demand from improved fuel efficiency and electrification would be overpowered by increased demand for car travel as the middle class grows in emerging economies.

Regardless of their projected timeframes for peak oil demand, major oil and gas companies see renewables as a fast growing component of the energy sector and are positioning their companies in that space accordingly. There also appears to be a consensus that low-cost oil producers will have a significant competitive advantage during periods of slow demand growth. With the anticipated slowdown in the demand for oil, some analysts predict natural gas will emerge as the dominant energy source

over the next 20 years, supplying 27% of the energy demand, with various renewable sources supplying approximately 50% (Ambrose, 2017) (DNV GL, 2017).

As discussed previously for mineral commodity prices, the world price of oil is based on a complex set of factors, including supply, demand, geopolitics, and speculative investment. Oil prices, like mineral prices, are prone to price shocks and cycles leading to long-term uncertainty. Unlike oil, however, challenges to date with transportation have limited the scope for natural gas to be a global commodity and for convergence to a global price for natural gas. This could change with Liquefied Natural Gas (LNG), which facilitates marine transportation of natural gas and represents a "supply source mobile enough to plug supply and demand gaps in international markets" (Bresciani, Inia, & Lambert, 2014).

From 2002-2008, the world price for oil saw a generally steady increase from approximately $25/barrel to a high of approximately $145/barrel in mid-2008 (Macrotrends, 2017). Over the following 6 months, oil prices declined dramatically to a low of approximately $35/barrel. Oil prices rebounded from 2009-2011 and leveled out near $100/barrel until June 2014.   By Jan 2015, prices had dropped to approximately $45/barrel. In early 2016, the price of oil dropped further to just under $30/barrel, and in the second half of 2017 prices rose to approximately $65/barrel.   There is debate among analysts about whether the recent oil price changes are cyclical, as had been thought to be the nature of the oil industry, or structural, corresponding to a period when oil prices will be lower for much longer (Fattoch, 2016).

(4.1) Digitalization in Oil and Gas

With this tumultuous backdrop, digitalization of the oil and gas industry has been proposed as a necessary radical transformation of the industry (PwC, 2016a). Digital technologies are seen as key to transforming operations in order to create new opportunities for profits following the latest period of oil price decline (Choudhry,

Mohammad, Tan, & Ward, 2016). It has been suggested that digital technology has traditionally been employed by the oil and gas industry as a means of cost reduction (PwC, 2016a). It could, however, provide much more, including enabling new approaches to operations that would allow companies to continue to produce "oil and gas, but in ways that will be virtually unrecognizable".

Other drivers of a digital transformation in the oil and gas industry include a push of "oil and gas operators into new frontiers – deeper waters, more remote reservoirs and unconventional plays – that were once out of reach" (EY, 2016). In the Canadian context, digitalization may be essential for developing deep-water, far-offshore oil and gas resources, such as those being pursued by Statoil and Husky Energy in the Flemish Pass Basin, located approximate 500 kilometres off Canada's east coast (Statoil, 2017b) (Husky, 2017).   For such far-offshore development, it will not be practical to transport the large numbers of workers back and forth from production platforms as required using conventional approaches to operations.

A significant collaboration based in Norway, which included Statoil, BP, IBM, and other industry and academic partners, was carried out from 2006-2014 with the objective to "develop new methods and tools for 'integrated operations', which can be embedded in improved work processes in the oil companies and enhanced products and services from the suppliers" (CIOPI, 2006). In 2016, Statoil opened a Joint Operations Centre in Bergen, Norway to utilize integrated operations in support of safety, vessel optimization, emergency response, supply logistics, and machinery condition monitoring across multiple operating oil fields. Petroleum Research Newfoundland and Labrador (PRNL), an organization that funds and coordinates research on behalf of the east-coast offshore oil and gas companies, identified integrated operations as a priority area for research and development investment by its member companies (PRNL, 2017). In the case of Newfoundland Labrador, PRNL highlighted an opportunity to leverage expertise

locally in areas such as ocean and subsea technology, remote sensing, and autonomous underwater vehicles (AUVs).

A recent report by Accenture highlighted digitalization as a key enabler for the oil and gas industry with respect to value creation in the future (Accenture, 2017). Digitalization could help industry deal with increasing challenges in attracting talent and in meeting higher expectations to reduce climate change impacts. While the oil and gas industry has adopted digital technology as it has matured, there is considerable variability among upstream operators with respect to the extent to which digitalization has occurred (PwC, 2016b).

Regardless of the uptake to date, digitalization in the oil and gas industry is anticipated to bring structural changes similar in impact on costs and operations to that felt by the introduction of horizontal drilling and hydraulic fracturing (Endress A. , 2017a).   It is expected oil and gas operations will evolve from primarily manual operations requiring large numbers of people on a production platform to more automated operations, where a small number of highly trained generalists work on a remote platform connected to sophisticated mission support in much the same way as astronauts work on the space station.

Digital technology could enable improved real-time monitoring of the offshore operating environment, leading to better operational decision-making; lower operational risk; positive impacts on health, safety, and environment; and enhanced productivity.   In the near term (i.e., 3-5 years), the top digital technology focus areas are anticipated to include big data, analytics, internet of things (IoT), and mobile devices, while the subsequent 5-year period is expected to see a focus on robotics, autonomous vehicles, artificial intelligence (AI), and wearable technology (Accenture, 2017).

Statoil recently articulated a vision of being a global digital leader and outlined a roadmap for seven specific digitalization projects to be executed under a Digital Centre of Excellence (Statoil, 2017a). For Statoil, the areas of particular interest under its digital roadmap include digitalization of work processes, advanced data analytics, robotics, and remote control. Similarly, Shell embraced digital innovation with priority areas for upstream oil and gas operations, including 3-D printing, robotics, advanced analytics, and high performance computing (Shell, 2017a). For BP, artificial intelligence could make it possible to "combine datasets about areas such as flow rates and pressures and equipment vibration with data from the natural environment, such as seismic information and ocean wave height, to transform the way we run and optimize our operations" (BP, 2016a). Chevron sees automation of their operations, generating better data, and translating that data into useful information as enabling the company to "operate more safely, reliably and efficiently; reduce costs; recover more resources; and better manage risks", thereby helping to realize the potential value from billions of dollars of assets across the company (Chevron, 2017).

Remote control of oil production systems is not new. In 1975, Exxon demonstrated remote control of a submerged production system in the Gulf of Mexico (New Scientist, 1975). Modern remote drilling operations, which utilize distributed sensors, high-speed communications, and data-mining techniques to facilitate access to deeper, more remote, and more complex resources, have been demonstrated over the last decade (Leber, 2012). Chevron estimated such technology could lead to productivity improvements of 8% and recovery improvements of 6% (Chevron, 2017). Collaborative work environments, which utilize high-quality videoconferencing, smart wells, reservoir surveillance solutions, fibre optics, and real-time production monitoring, are commonplace in the oil and gas industry (Shell, 2017b). This technology allows field workers to interact with specialist colleagues who remotely monitor field conditions in order to optimize operations. The Perdido project in the Gulf of Mexico was Shell's first fully integrated digital oil field (Perrons, 2010).

There are also examples of robotic-type systems being used within the upstream oil and gas industry. These include tele-operated "iron roughnecks" which allow drillers to handle drilling operations remotely as pipe segments are connected or disconnected automatically, increasing the safety and efficiency of a once dangerous job (RIA, 2017). This equipment operates in much the same way as the tele-operated LHD described for the underground mining industry. Schlumberger, a major oil and gas service provider, offers a range of robotic and autonomous vehicle services related to data collection in the offshore environment (Schlumberger, 2016). Applications include hydrocarbon detection and mapping, marine geomatic surveys, seismic surveys, metocean data collection, sea mammal monitoring, and environmental monitoring. Robots and unmanned vehicles have also been reported for monitoring, inspecting, and mapping applications by the oil and gas industry (BP, 2014) (ExxonMobil, 2016) (Torres, 2016). BP and Oceaneering partnered on a large-scale AUV trial in the Gulf of Mexico for surveying pipelines and subsea infrastructure using a variety of marine autonomous systems, including remotely operated vehicles (ROVs), wave and underwater gliders, and autonomous surface and underwater vehicles (BP, 2016b).

Advanced robotic offshore drilling systems have also been developed, although there is reluctance on the part of industry to embrace full automation. Instead, "smart automation technology informs human drillers who ultimately take all key decisions" (Vella H. , 2016). One of the limiting factors for the uptake of automated drilling technology is the large number of capital intensive, but underutilized, conventional floating rigs. Fully automated drilling would require newly designed and constructed drilling rigs which are not likely to be built in the foreseeable future.

As discussed previously for the mining industry, managing the challenges and opportunities of digitalization requires oil and gas companies to have digital strategies, rather than ad-hoc digital initiatives. An important step toward developing effective

digital strategies is leadership commitment. A recent survey showed only 3% of oil and gas companies have established senior executive-level positions to "navigate the open sea of the digital transformation" (Endress A. , 2017b).   In the case of the Shell Perdido digital oilfield project, digitalization "happened more completely and quickly than expected because of the emergence of champions who understood the value of these technologies" (Perrons, 2010). It was also observed that the "journey toward becoming an integrated digital oilfield would not have yielded the highly positive outcomes that it did without the strong support within the Perdido team, the relevant Shell E&P communities, and both BP and Chevron".

(5.0) Other Considerations

There are a number of other important factors to be considered for digitalization of Canada's mining and oil and gas industries. First, these industries are subject to extensive regulation, both provincial and federal, that may affect the rate of technological progress and innovation.   Secondly, digitalization will have an impact on the level and nature of employment, with implications for education and training programs required for the future workforce, for the `value proposition' for communities in resource regions, and for levels of `technological anxiety' among the general public. Thirdly, advances in digital technologies are expected to come primarily from outside of the extractive industries, and this will require reconsideration of traditional supply chains and the role of small and medium-sized enterprises (SMEs) and other innovators and approaches to innovation.

(5.1) Regulation and Technological Progress

The mining and oil and gas industries are subject to heavy regulation because some of their activities have the potential, if not carried out properly, to result in serious and lasting harm to the environment and to worker health and safety.   In addition, there could be harm to nearby communities and to public health.   Therein lies a conundrum. There are competing pressures to innovate, as the operating environments for

extractive industries become more challenging and beyond conventional approaches, and to strengthen regulations to manage the increased risks associated with operations in those more challenging environments (LR, 2015b). The rate of regulatory change is generally much slower than the rate of technological change.

As a consequence of the potential for significant harm, extractive industries are often subjected to `prescriptive' regulations that detail how their activities must be carried out. This is in contrast to more `performance-based' or `outcomes-based' regulations that define desired outcomes or levels of performance and leave industry to determine how to carry out their activities while ensuring performance targets are met. The latter approach to regulation has been proposed as being more amenable to the adoption of new technologies (NRCan, 2013).

In 1996, the Government of Canada confirmed provincial jurisdiction for regulation of mining developments through its Minerals and Metals Policy (NRCan, 1996). While the Minerals and Metals Policy calls for regulation to be performance-based rather than prescriptive, approaches to regulation of mining activities vary widely across Canada.

In Canada, there is an initiative underway – Frontier and Offshore Regulatory Renewal Initiative (FORRI) – to modernize the regulatory process for oil and gas activities that are under the jurisdiction of the federal government (NRCan, 2017d). Input from Canadian industry into the FORRI consultation process called for a commitment to effective implementation of a performance-based regulatory system supported by guidelines and other tools consistent with a performance-based management approach (CAPP, 2016).

For onshore oil and gas in Canada, regulation is under provincial jurisdiction. In Alberta, new and unique scientific and technological challenges of unconventional oil and gas development, as well as the need for new technologies and approaches to operations, provided the impetus to consider "risk-based and play-focused" approaches to

regulation of unconventional resource developments (ERCB, 2012). A public review of potential unconventional oil and gas development in Western Newfoundland recommended a regulatory framework with an appropriate mix of performance-based and prescriptive regulations (Gosine, Dusseault, Gagnon, Keough, & Locke, 2016). Such an approach would allow for evolution of regulations as new knowledge and experience are gained, and would be supportive of innovation and the adoption of new technology.

A study of green mining technology highlighted that the "potential for delays in the environmental assessment process with introducing a new technology that does not have a demonstrated track record acts as a deterrent for some mining companies" (MNP, 2011). Furthermore, the study highlighted that many mining companies may not be able to afford the time and resources needed to generate the verifiable evidence required by regulators about the performance of a new technology. As a consequence, industry tends to use proven technologies, rather than risk delays or non-approval of innovative technology applications. A study of the impact of environmental regulations on innovation in the Australian oil and gas industry suggested "the less prescriptive nature of the regulatory approach taken by the Queensland government is supporting innovation" and that companies are "striving to make their operations very environmentally robust and going beyond compliance" (Ford, Steen, & Verreynne, 2014).

In the context of oil and gas regulations, it was proposed that "regulators must create an environment that enables innovation" and they "must engage with technical experts from industry to identify new ideas for supporting innovations, be open and flexible to pilot testing activities and employing a more outcomes-based approach to regulation in order to support innovation " (EY, 2015a). This call for closer cooperation between regulators and other stakeholders in order to improve the regulatory framework and to facilitate the required innovation is not unique to Canada. Lloyd's Register, a global engineering organization, proposed "a blend of the best expertise from business,

academics, regulators and governments" would lead to a better understanding of risks, while "a blend of design skills, application of science, operations, risk appetite and consequence together with legislation regimes" would lead to more appropriate regulations (LR, 2015b).

Within the offshore oil and gas industry, international classification societies, such as Lloyd's Register, the American Bureau of Shipping, and DNV-GL, set and monitor standards for the design, construction, operation, inspection, and maintenance of offshore structures and vessels. These classification societies feature in Canadian offshore petroleum regulations and they play a critical role in ensuring safety and environmental performance of offshore operations.

Recent foresight exercises by the Lloyd's Register Foundation (LRF) considered the emergence of big data, analytics, robotics, and autonomous systems (LRF, 2014) (LRF, 2016). These exercises reviewed the implications for the industries Lloyd's Register serves and for the work done by Lloyd's Register in the certification and assurance of industry assets.

With respect to big data and analytics, LRF proposed a paradigm shift towards data-centric engineering where "data considerations are at the core of engineering design" with resulting improvements in "performance, safety, reliability and efficiency of assets, infrastructures and complex machines" (LRF, 2014). A range of data management issues, including standards, collection, storage, and security, would be part of the engineering life-cycle and would impact on approaches to designing, manufacturing, maintaining, and decommissioning assets. The data itself would be an asset, requiring verification of the pedigree, quality, and accuracy of data. The certification and quality assurance roles played by organizations such as Lloyd's Register would need to adapt accordingly if a data-centric engineering approach was adopted by industry.

In terms of robotics and autonomous systems (RAS), LRF highlighted critical issues such as the dependability and appropriateness of action of RAS, methods of RAS `learning', exchange of control between human operators and RAS, system security, public trust and ethical frameworks for applications of RAS, and anxiety about employment disruption (LRF, 2016). Also, the need for "living laboratories in existing infrastructure" was highlighted as a means of providing the necessary focus to undertake basic R&D, perform first demonstrations of prototypes, and de-risk and certify systems that could be put into normal operation. This requires regulatory frameworks that are supportive of innovation and approaches to understanding and managing the associated risks.

(5.2) Technology, Employment Impacts, and Education and Training

The fusion of advanced technologies and the "transformation of entire systems of production, management, and governance" may disrupt labour markets (Schwab, 2016). At this point there is considerable uncertainty about the impacts on the number of jobs and the timing of such impacts, although there is general agreement that the nature of work will change significantly. There are also growing concerns, or `automation anxiety', about the "replacement of complex cognitive tasks and human decision making by algorithms, machine learning and other computational techniques" (Sussex, 2017).

Schwab noted that if automation substitutes for labour, "the net displacement of workers by machines might exacerbate the gap between returns to capital and returns to labor" (Schwab, 2016). Some researchers believe the impact of automation on jobs would be considerably larger than what many analysts have been projecting (Ticoll, 2017).   Schwab also noted, however, the impacts are unclear and the application of automation could lead to an overall increase in safer and more rewarding employment opportunities (Schwab, 2016). Key issues, however, include the locations of these new jobs, as well as the required education and skill levels. For extractive industries, there is a question about whether new jobs that could result from digitalization would benefit individuals in resource communities and regions.

A recent report from the International Federation of Robotics (IFR), an advocacy group for robotics, proposed "robots complement and augment, rather than substitute for, labour and in doing so, raise the quality of work and the wages of those fulfilling new tasks" and "automation has led overall to an increase in labour demand and positive impact on wages" (IFR, 2017).   The IFR report proposed that less than 10% of jobs involving manual labor could be fully automated, and robots may complement and augment manual labour for some jobs. Middle-income/middle-skill jobs would be prone to loss through automation, while the demand for high-skill jobs would increase, as would wages. This is consistent with the perspective that "automation does indeed substitute for labor—as it is typically intended to do. However, automation also complements labor, raises output in ways that lead to higher demand for labor, and interacts with adjustments in labor supply" (Autor, 2015). Between 2010-2015, the IFR reported that the U.S. automotive industry installed 60,000 new robots, while there was an overall increase in employment of 230,000 jobs in the industry over the same period (IFR, 2016).   The report, however, did not discuss other factors, such as increases in production, that may have influenced overall employment numbers.

Some practitioners refer to the next generation of machines that work with and assist workers, rather than replace them, as `cobots' or collaborative robots (Hollinger, 2016). Collaborative robotics is particularly attractive for work activities for which human judgment is required and where the physical environment presents ergonomic challenges. For certain job activities, studies have shown human-robot teams are more productive than humans or robots working alone (Tobe, 2015).

In automobile assembly plants, some industrial robots have been replaced by cobots with the primary objective to improve the safety and ease of tasks for workers on assembly lines. Cobots have been proposed as part of the solution to attracting and retaining the required workers for the manufacturing industry at a time when many

current workers are retiring (Gonzalez, 2016). Cobots could also be a viable technology to support the manufacturing operations of smaller suppliers that need greater flexibility and portability of technology than is typically provided by large-scale, fixed-in-place robotic manufacturing systems.

Autor stated "journalists and even expert commentators tend to overstate the extent of machine substitution for human labor and ignore the strong complementarities between automation and labor that increase productivity, raise earnings, and augment demand for labor" (Autor, 2015). Headlines in Canadian popular press, such as "Driverless trucks could mean 'game over' for thousands of jobs", fuel concerns about the impacts of automation on employment (Grant, 2015).   The article highlighted Canadian mining and oil and gas companies as early adopters of automated truck technology.

Another recent study suggested that while almost half of all work activities across the economy could be automated, less than 5% of all occupations could be automated using existing technologies (Manyika, et al., 2017).   It was estimated 60% of all occupations have at least 30% of their activities that could be automated, with "physical activities in highly structured and predictable environments, as well as the collection and processing of data", being the activities most easily automated.

Manyika presented a case study of the potential for automation in an oil and gas control room. The proposed advantages of automation included "better personnel safety, greater efficiency, higher throughput, improved agility, and cost reductions from relocating operators from remote sites to centralized offices". Furthermore, technologies such as intelligent sensors and analytics could "enable predictive maintenance, which is just one-quarter the cost of reactive maintenance".   It was estimated 80% of the value created from automation of the control room would result from performance gains, while 20% would result from labour substitution.

Other analysts suggested better utilization of existing computing technology in the oil and gas industry could see positive financial impacts of up to $3 billion for a major oil and gas company (Ward, 2016). Of this amount, $1 billion in savings would accrue from more efficient deployment of engineering resources, allowing companies to stay ahead of the increasing challenge to find talent.

While some jobs within oil and gas companies would be eliminated by automation, there would be an increase in demand for digitally literate employees, such as data analysts and engineers (Kline, 2017). Along a similar theme, Accenture predicted digitalization will both demand and enable a fundamentally different workforce in the oil and gas industry and, while some manual jobs will be replaced by digital technology, other "more digitally-oriented jobs will be created to take their place" (Sloman, Holsman, & Cantrell, 2014). The Lloyd's Register Foundation (LRF) proposed the changing nature of the workforce would further challenge all levels of the education system, from the primary and secondary school system, through post-secondary institutions, to organizations offering ongoing training and education to professionals in industry (LRF, 2016).

For the mining industry, the overall employment impacts as a result of digitalization are also subject to debate (Davis, 2017).   In the future, as a result of widespread digitalization of field operations and back-office processes, some analysts believe digital mining will involve far fewer people (Deloitte, 2017). The future workers would also have different skillsets than required today by the mining industry. Currently, local employment is a critical part of the value proposition that mining companies are expected to deliver upon throughout their operations in communities with extractive resources.

Whether a 25-year vision for autonomous mining can be realized is an open question. A study led by the University of Queensland considered the social dimensions of autonomous and remote operations and concluded that "autonomous technologies seem likely to reduce additional jobs created through mining industry growth, rather than leading to a net reduction in mining employment" (McNab, Onate, Brereton, Horberry, Lynas, & Franks, 2013). The study findings noted that some jobs, such as driving trucks or manually operating underground equipment, would disappear, while new jobs, which would be increasingly concentrated in urban areas, would require different competencies. Benefits of automation were proposed to include improved safety and reduced risk for workers.

One challenge for automation is the integration of automated technology into existing mine sites (Jensen, 2016). Others have noted there will always be a need for infrastructure to support people working underground since "sooner or later equipment always breaks down and somebody has to go and fix it" (Vella H. , 2017). Within existing underground mining operations, large equipment is dismantled and rebuilt underground so there is a need for in-situ repair and maintenance of equipment, including automated vehicles.

Dramatic adjustments to employment in an industry can provide the impetus for innovation and entrepreneurship by those who are displaced. Following a major downsizing by the mining industry in Sudbury in 1981, a number of "unemployed miners, armed with tacit knowledge of the major mining companies, created small and medium-sized enterprises (SMEs) to serve the local mining industry" (Hall, 2017). Today, there are over 300 supply and service companies in the Sudbury area, employing approximately 13,500 people.

Whether the Sudbury experience will hold up through a workforce disruption from digitalization is an open question. A release of labour as a result of widespread

digitalization of the mining and oil and gas industries would be complicated by a significant knowledge gap with respect to digital technology and digital innovation among those displaced. It is unlikely that knowledge of a pre-digitalized industry would be a sufficient base upon which to offer advanced technical services to a digitalized industry. Unlike the Sudbury experience, the expertise needed by extractive industries following digital disruption would be found, to a significant extent, outside of the extractive industries, in other sectors and locations that are more proactive in advancing digital technologies and their applications. Furthermore, the current alignment of education and training programs at some post-secondary institutions to meet the current employment needs of extractive industries may fall short in terms of positioning young people with an affinity to resource regions for careers in digitalized extractive industries.

As with projections about the changing nature of employment in the oil and gas industry, mining industry analysts have pointed to the need to "build a workforce of the future by attracting highly diverse people with a new set of digital skills" (Deloitte, 2017). The mining industry "will increasingly find themselves competing for scarce technical talent with more attractive pure play digital disruptors".

A recent survey of over 2000 companies in 26 countries about Industry 4.0 identified the lack of training and a digital culture deficit among existing workforces as the top challenges faced by companies (Geissbauer, Vedso, & Schrauf, 2016). The need to address education and training requirements includes upgrading knowledge and skills for existing workforces, as well as preparing university and college graduates better for careers in digitalized industries.

Understanding the employment impacts of digitalization of the mining and oil and gas industries will be important, both to the companies and to the communities and regions in which there are resource developments. For mining and oil and gas developments,

an important element of the historical value proposition is local employment, including direct, indirect, and induced employment, across all education and skill levels. Other elements include the consumption of local goods and services and revenues from taxes and royalties.

For extractive resource development projects in Canada, there are negotiated benefits agreements that define how communities and regions participate in the employment and economic activities arising from resource development projects.   As an example, for the Hebron offshore oil and gas development project, the benefits agreement stipulated a minimum number of person-hours of engineering and construction work had to be done in Newfoundland and Labrador (NL) prior to the start of oil production (Hebron, 2008). Other requirements included financial support for the NL supply and service sector to engage with the engineering offices of the proponents or their out-of-province suppliers, and a defined level of R&D expenditure by the proponents within NL over the lifetime of the project.   The proponent's benefits commitments are monitored by the Canada-Newfoundland Offshore Petroleum Board (C-NLOPB) and the proponents file public quarterly and annual reports regarding their performance in meeting their commitments (HMDC, 2017).

In the context of mining in Canada, impact and benefits agreements (IBAs) are negotiated between mining companies and Aboriginal communities to "document in a contractual form the benefits that a local community can expect from the development of a local resource in exchange for its support and cooperation" (IBA RN, 2006). The IBAs typically address issues such as environmental protection, including special concerns about wildlife; protection of Aboriginal social and cultural values; education, training, and employment; health and safety; business opportunities; Aboriginal access to the project site; financial arrangements; and dispute resolution mechanisms (Vale, 2017). Aboriginal communities "hold inherent rights in their traditional territories, and thus should share in employment and financial benefits from development projects on

those lands" (Kielland, 2015). Generally, IBAs are in addition to resource revenue sharing arrangements between project proponents and governments.

While benefits agreements typically deal with direct employment requirements, the second-order effects associated with changes in employment levels as a result of digitalization also need to be understood. For example, there would be income tax impacts associated with changes in employment levels or changes to local salaries paid by industry as a result of increased automation (Balch, 2016). A reduction in direct employment in a region would also result in a reduction in induced employment in that region.

With the rise of the concept of 'social licence to operate' (SLO), which is sometimes referred to as `social licence' or `public confidence', the impact of digitalization on employment and other elements of the value proposition will be particularly important to understand (Mann & Cosbey, 2016). For both mining and oil and gas companies, developing and maintaining a trust relationship with the communities in which they operate is recognized as a reality of doing business in the future (Sanyal, 2012) (Latimer, 2015). A University of Queensland study identified key "social dimensions of automation", including the structure of the workforce and workforce management practices; workplace and public health and safety; mining-related regional development opportunities; and Aboriginal employment and community relations (McNab, Onate, Brereton, Horberry, Lynas, & Franks, 2013).

Depending on the ultimate impact of digitalization of extractive industries on the employment component of the value proposition, there may need to be a rebalancing of the weighting on the other historical components or the introduction of new components of the value proposition. New components could include introducing more local downstream processing of extracted resources, developing value-added products that would be manufactured locally, supporting more widespread infrastructure

improvements that benefit communities and operations, and increasing knowledge and technology transfer to local communities that could be more widely utilized in other sectors of the economy (Cosbey, Mann, Maennling, Toledano, Geipel, & Brauch, 2016). Policy makers will need to be engaged early in order to mitigate the negative social impacts of employment loss (LRF, 2016). Given the increased attention generally in the media, including social media, regarding the impacts of automation on the future of work, securing public confidence for extractive resource projects will be further complicated by automation anxiety.

(5.3) Technology from Other Sectors

The enabling digital technologies and approaches to their integration into systems are common across many industry sectors, albeit with some adaptations tailored to sectoral differences. Learning from other industries that have adopted new technologies and approaches to their application will be important (Jacquand, 2017). In particular, technologies developed and deployed for the manufacturing, forestry, agriculture, automotive, aerospace, biotechnology, financial technology, and gaming sectors may be adapted and adopted for applications by extractive industries.

By way of illustration, new financial technologies being employed in the financial sector may play important roles in the future of extractive industries (Koeppen, Shrier, & Bazilian, 2017). Specifically, blockchain technology may be utilized in applications to increase transparency and provide efficiency in regulatory compliance, to enhance data security, to facilitate smart contracts, and to improve logistics. Such technology has the potential to improve management of supply chains for extractive industries (IBM, 2016). This technology may also make it possible for a proven ore reserve to be converted into digitized assets prior to it being mined. This could include orebits that can be bought and sold electronically (BusinessWire, 2017).

Such technology may also facilitate new value propositions for communities in which extractive industries operate in order to secure the social and economic futures of those communities. In other words, it may be possible to generate financial revenue streams into communities in the absence of current production. In the traditional mining lifecycle, mining company pensions, which guarantee revenue being paid to former company employees long after active mining has ceased and the mining company has left the community, have been a critical social and economic stabilizer for single-industry mining towns. In some cases, these pensions may have helped avoid `ghost-town' outcomes for communities. As the requirement for ongoing public confidence in extractives industries in Canada becomes more widespread, digital technology may support industry in delivering an early value proposition to communities and in having new value proposition options at later stages of projects.

Unlike 20 years ago when autonomous vehicle technology was being pioneered by the mining industry to improve productivity and safety in a niche market, today this technology is being advanced by the automotive industry and by technology companies, such as Ford, General Motors, Tesla, Uber, Google, Blackberry, and Apple, for much larger consumer markets (Davies, 2017) (Tesla, 2016) (Marshall A. , 2017a) (Blackberry, 2017) (Moren, 2017). In particular, research directed toward systems that enhance the safety of humans (e.g., other drivers and pedestrians) on roads utilized by autonomous automobiles could also be useful for introducing automated mining robots into established mines that use conventional approaches to production (Condliffe, 2016). The experience of the automotive and manufacturing industry in the application of collaborative robotics, or cobots, is also particularly relevant and important to consider. Regardless of whether full automation can ultimately be achieved, the complex nature of the physical environments for both mining and offshore oil and gas development will necessitate close interaction and collaboration between humans and machines for the foreseeable future.

(5.4) The Role of Small and Medium-sized Enterprises (SMEs)

With the exception of the mineral exploration sector, modern extractive industries tend to be dominated by large global firms. The last commodities boom escalated mergers and acquisitions among already highly concentrated companies. Many of these deals were over-leveraged and based on unrealistic expectations for commodity markets. In some cases, individual units and properties from these ventures have been dismantled and sold off.   Historically, conservative and risk-averse mining and oil and gas companies looked toward similarly conservative and risk-averse supply and service providers. These characteristics are not conducive to innovation and may impede the adoption and adaption of disruptive technologies by extractive industries (Brownlee, 2016).

In the case of some large corporations, such as Lockheed and Apple, a "skunk works" approach has been used to provide key technical and scientific staff with the time and resources to engage in breakthrough innovation away from normal company operations (May, 2012). It is also the case that disruptive technologies are often driven by smaller, more agile, and less traditional firms, many of which are not part of the supply chains for large extractive industries.   As a result, large extractive industries may not benefit from the disruptive technologies originating from these smaller innovative companies.

Unfortunately, many SMEs do not have a good understanding of needs of the larger companies nor their procurement processes. This lack of understanding is perpetuated by the fact there are limited mechanisms for interaction between SMEs and the large operating companies and their suppliers. Similarly, decision-makers in extractive industries and among their larger suppliers are often unaware of the technology and capacity available through SMEs.

Given the prospect for widespread application of disruptive technologies in consumer products and across industry sectors, there is potential for higher levels of innovation

and entrepreneurship, leading to new opportunities for SMEs and for the creation of new technology-based companies (Manyika, Chui, Bughin, Dobbs, Bisson, & Marrs, 2013).   The need for extractive industries to embrace disruptive technology may lead to better, more effective engagement between extractive industries and technology developers, including SMEs and other innovators, traditionally operating outside of the supply chains for mining and oil and gas companies. New ways of establishing collaborations among key players need to be explored by extractive industries.

Digitalization provides an opportunity for innovative Canadian technology to enhance the viability of Canada's extractive industries and to create export opportunities for Canada's technology companies, particularly SMEs.   With respect to enabling export opportunities for SMEs, however, Canada is challenged. As noted by the Advisory Council on Economic Growth, "in general, Canadian corporations are relatively slow to adopt new technology and seem reluctant to buy from young or smaller firms" (ACEG, 2017). The Advisory Council went on to suggest that larger companies could support growth of SMEs, both by acting as early customers and by connecting SMEs with other companies in their supply chains. In order for Canadian SMEs to be successful in participating in a global supply chain for the energy industry, it was proposed government must "use policy to ensure stable, robust domestic demand in target energy sectors and consequently spur industry innovation" (McKinsey, 2013).

(5.5) Other Approaches to Innovation

It has been long argued that innovation is a social process within which people interact to develop ideas and knowledge that underpin marketable products and services (Maxwell, 2003). As discussed by Smith et al., "successful innovative firms are usually those which are open to their environments. That is, they engage in interactive learning involving other institutions: partners, rivals, and a wide range of other knowledge-creating and knowledge-holding institutions" (Smith, Dietrichs, & Nas, 2015).   The "easy wins" with respect to incremental improvements have largely been achieved, and

ground-breaking, transformative innovations will come "from looking at the world from several perspectives at once - engineering, finance, design, marketing, moral, legal, and so forth - and synthesizing them into something that's greater than the sum of the parts" (Jarvis, 2016).

Innovation approaches from other sectors need to be considered, such as the Hacking Health movement, established in 2012 in Montreal and subsequently expanded internationally. This `open innovation' approach brings fresh thinking to addressing challenges in the healthcare sector and to engaging people with the knowledge and skills, often from outside the sector, needed to advance healthcare into the 21st century (Lindeman, 2015).  A `hackathon' brings together health professionals, policy makers, technology providers, technology developers, students and faculty, entrepreneurs, and investors to generate fresh ideas, to share insights, and to develop creative solutions (Hacking Health, 2017). Extractive industries recently started to explore this more open and creative approach to innovation (OGA, 2016) (CMIC, 2017a). An upcoming 54-hour open innovation hackathon in Vancouver will consider three `challenges' involving the use of digital technology and analytics to improve the performance of discrete components of mining operations (Unearthed, 2017).

Another open innovation approach involves `crowdsourcing' solutions to major challenges by engaging a broad range of expertise and unconventional thinking. In the case of the oil and gas industry, Sweden's Draupner Energy was established in 2015 to "leverage crowdsourcing and networked innovation over an internet platform to identify and deliver novel ideas, innovative project solutions, develop energy and carbon capture and storage projects, and move them to market" (Draupner, 2017). In 2015 and 2016, Statoil and General Electric co-sponsored global open innovation challenges to solicit concepts for reducing the amount of sand and water used in unconventional oil and gas development (GE-Statoil, 2015) (Statoil-GE, 2016). Statoil recently issued an

open innovation challenge to consider how digitalization could change how energy is produced and consumed (Statoil, 2017c).

Within the Canadian mining industry, the CEO of Goldcorp, inspired by the open-source software movement, believed that crowdsourcing new ideas about where to dig could "speed up exploration and improve his odds of discovery" at an underperforming mine in Ontario (Tischler, 2002). Goldcorp launched an innovative challenge that made all of the company's proprietary geological data available on the company's web site. The challenge let outside experts have access to the data to identify "where the next six million ounces of gold" would be found in return for a $575,000 prize (ideaconnection, 2009). It was estimated that the challenge "cut two, maybe three years off the company's exploration time. And the worth of this gold has so far exceeded $6 billion in value". In 2007, Barrick Gold launched its Unlock the Value Program to challenge researchers from around the world to liberate 180 million ounces of silver that was contained in gold reserves in the Veladero mine in Argentina (Barrick, 2007). The Barrick challenge stated that "experience in mining is not required because we are looking for innovation and new approaches".

In 2015, Integra Gold Corporation, which is now owned by Eldorado Gold, announced it was making 70 years of prospecting data available on the internet in order to "let people who aren't usually involved in exploration bring creative data analysis methods to the table" and to "inject some much-needed innovation into an industry that's struggling with high costs and low commodity prices" (FP, 2015). Data collected from a growing number of digital devices deployed across oil and gas and mining operations could provide a rich source of raw material for crowdsourcing new internet of things (IoT) products and services (Ratzesberger, 2015).

Other models for promoting innovation include longer-term (e.g., 12-18 months) design competitions to develop and demonstrate game-changing technology. An early

example of the "prize challenge model" was the DARPA Grand Challenge, an autonomous vehicle challenge, with a vision to "encourage new waves of research and development that will spur continued innovation, encourage commercial investment, and lower the cost of advanced technologies" (DARPA, 2014). Reflecting on the impact of the challenge program 10 years after it was launched, DARPA concluded "the fresh thinking they brought was the spark that has triggered major advances in the development of autonomous robotic ground vehicle technology in the years since".

A more recent example of the prize challenge model is the Hyperloop Pod international competition that targeted a new `fifth mode' of transportation (SpaceX, 2017). This international student competition was launched in response to a proposal to build a conventional bullet train as a solution to statewide mass transit in California (Musk, 2013). From over 1000 teams that initially applied for the competition, 115 teams submitted designs in January 2016 and 30 were selected to build their designs and to do preliminary testing on the Hyperloop track in January 2017. A full competition among 24 teams was held in August 2017, and a further competition is set for mid-2018. Another illustration of this approach is the 8th Annual Robotic Mining Competition that will be hosted by the U.S. National Aeronautics and Space Administration (NASA). This competition will bring together 50 U.S. university teams (NASA, 2017).

In 2017, the Government of Canada launched the Innovation Superclusters Initiative (ISI) to "accelerate the growth and development of business-led innovation superclusters in Canada, translating the strengths of our innovation ecosystems into new commercial and global opportunities for growth and competitiveness" (ISI, 2017). Both the mining and oil and gas industries aspire to lead superclusters, including a mining cleantech cluster and a digital oceans cluster involving the oil and gas industry (CMIC, 2017b) (ResearchInfosource, 2017).

Both of these supercluster initiatives would see major investments by industry and government to bring together an array of collaborating companies and organizations to advance innovation and move Canadian industry into a world-leading position. For example, the mining cleantech supercluster is an "industry-led, multi-stakeholder consortium comprised of four existing clusters, which, combined, represent 11 large companies (including eight resource companies), 13 post-secondary institutions, 42 SMEs and 25 other support organizations" (CMIC, 2017b). The digital oceans supercluster would bring the offshore oil and gas industry together with other ocean industries to advance technologies that could be developed and adapted across industries (ResearchInfosource, 2017).

(6.0) Mining and Oil and Gas: Digital Synergy

In terms of exploring the opportunities and challenges related to digitalization of extractive industries, there is tremendous synergy between the mining industry and the oil and gas industry, particularly between mining and offshore oil and gas production operations. Both mining and offshore oil and gas are global industries involved in increasingly remote production operations in harsh environments that, by their very nature, modify the environment. Both the suppliers to these industries and the customers are international in scope.

Mining and oil and gas activities generate significant export value for Canada and employ, directly and indirectly, a large number of people with a wide array of expertise and skill. Employment represents a major part of the value proposition between the industries and resource communities. The employment impacts are national in scope and particularly important to regions where there is resource development.

Digital technology has the potential to improve, expedite, and reduce the cost for evaluation of resources. This could lead to new resource development projects that may not have been evaluated in the absence of improved resource assessment tools

that provide for the collection and processing of data that would previously not have possible.

The need to look to digital technology to increase operational efficiency in order to remain globally competitive could significantly change the levels and nature of employment in extractive industries, and, hence, the value proposition for governments and resource communities. This, coupled with a general anxiety among the public about impacts of automation technologies, further complicates the public confidence dynamic. Both the mining and oil and gas industries are already subjected to increasing challenges with respect to achieving and maintaining the public confidence necessary to carry out resource development projects.

Both sectors are capital intensive with long payback periods on investments. The financial risk, coupled with the cyclical nature of commodity pricing and price shocks, has contributed to weak investment in R&D and slow uptake of new technology compared with other innovative sectors of the economy.

Both industries have recognized the need to embrace digital technology if they are to survive, let alone flourish. There is an opportunity for these industries to work together to understand their digital futures, and those of their employees and the resource communities and regions in which these industries wish to operate.

For both mining and oil and gas companies, the future could include heavily digitalized assets (i.e., oil rigs, mining equipment), capable of high levels of autonomy and inter-asset cooperation, operating within challenging natural environments (e.g., a deep or remote mine or far offshore oil field) monitored using advanced embedded and remote intelligent sensor technology. These digitalized assets and intelligent sensor technologies could be connected via innovative communication systems to digital enterprises (i.e., mission control centres and other remote centres of excellence), where

experts would monitor production operations remotely, interact via technology with a limited number of field workers at production sites, and perform computational analysis on data collected from remote operations to optimize production, equipment maintenance, and asset utilization, while simultaneously ensuring regulatory compliance.   The digital enterprise could be part of a digital world in which technology would be deployed to improve supply chain management and resource management, to balance supply and demand for product, to manage contracting among project partners, and to help secure and maintain public confidence.

(7.0) Conclusions and Next Steps

The next generation of mining shares an emerging vision of increased digitalization of production operations with the offshore oil and gas industry of the future. Given the importance of the mining and oil and gas industries to the Canadian economy, it is critical that Canada prepares for the digital future of these extractive industries.

Challenges resulting from digitalization of these industries, however, must be identified, understood, and addressed by a diverse range of stakeholders. Some of these challenges include integration with legacy production operations, impacts on employment and the nature of work, securing talent with the required education and skills, more complicated relationships with governments and communities, and being innovative while complying with regulatory requirements.

While deriving economic benefit from mining and the oil and gas resources could continue to be important to Canada, it will be critical for resources industries, and the supporting supplier and service companies, to understand emerging digital technology, as innovators, consumers, and exporters of such technology.   As part of the digital economy, modern mining and oil and gas companies may accrue benefits including increasing the safety of workers, improving environmental performance, protecting public health, improving productivity and efficiency of operations, shortening the

exploration-development-production cycle time, increasing reliability of equipment, and reducing capital infrastructure costs.

The challenges and opportunities from digitalization come at a time of considerable media hype about technologies such as artificial intelligence and automation. Some pioneers in the field, such as Rodney Brooks, have lamented the "hysteria about how powerful they will become, how quickly, and what they will do to jobs" (Brooks, 2017). Brooks did not suggest that there will not be challenges and impacts from these technologies, but these will not be as sudden or unexpected as some predict. Finally, as noted by Brooks, "almost all innovations in robotics and AI take far, far, longer to be really widely deployed than people in the field and outside the field imagine". This is not to say that stakeholders in Canada's extractive industries can afford to delay preparing for a digital future.

Globally, digital technology will transform extractive industries. For Canada, this provides an opportunity to lead in developing and commercializing the enabling technologies, in integrating these technologies into global operations, and in considering the broader socio-economic and regulatory consequences of digitalization of these extractive industries.

Digitalization of extractive industries in Canada will certainly pose opportunities and challenges for a diverse range of stakeholders. In addition to the operating and supply and service companies, individuals and communities will be affected by digitalization, as will governments and institutions (e.g., education systems, regional development organizations, unions, and regulators). Successfully addressing the opportunities and challenges will require early and effective engagement of all stakeholders that is informed by realistic digitalization scenarios, timeframes for their implementation, and assessment of the broader issues and impacts.

(8.0) References

Accenture. (2017). *Digital transformation initiative: Oil and gas industry.* Retrieved from World Economic Forum Web Site: http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/white-paper-2017-dti-oil-gas.pdf

ACEG. (2017). *Unlocking innovation to drive scale and growth*. Retrieved from Goverment of Canada Web Site: http://www.budget.gc.ca/aceg-ccce/pdf/innovation-2-eng.pdf

Ambrose, J. (2017). *Big Oil to be usurped by gas in little more than a decade, experts warn*. Retrieved from The Telegraph Web Site: http://www.telegraph.co.uk/business/2017/09/04/big-oil-usurped-gas-little-decade-experts-warn/

Armbrecht, A. (2015). *China is still king of commodity consumption*. Retrieved from World Economic Forum Web Site: https://www.weforum.org/agenda/2015/09/china-king-of-commodity-consumption/

Arnoldi, M. (2017). *Digitalised mining can allow for deeper mining*. Retrieved from Mining Weekly Web Site: http://www.miningweekly.com/article/digitalised-mining-can-allow-for-deeper-mining-2017-04-07/rep_id:3650

Atlas Copco. (2015). *Insight on automation*. Retrieved from Atlas Copco Web Site: http://www.atlascopcogroup.com/en/media/innovation-stories/2015/insight-on-automation

Autor, D. (2015). *Why are there still so many jobs ? The history and future of workplace automation (in Journal of Economic Perspectives 29(3) 3-30)*. Retrieved from MIT Web Site: https://economics.mit.edu/files/11563

Balch, O. (2016). *Automated mining will cost jobs and tax income: It's time for governments to act*. Retrieved from The Guardian Web Site: https://www.theguardian.com/sustainable-business/2017/jan/20/autonomous-mining-will-cost-jobs-and-tax-income-its-time-for-governments-to-act

Barrick. (2016). *Barrick and Cisco partner for the digital reinvention of mining*. Retrieved from Barrick Web Site: http://www.barrick.com/investors/news/news-details/2016/Barrick-and-Cisco-Partner-for-the-Digital-Reinvention-of-Mining/default.aspx

Barrick. (2007). *Barrick offers US$10 million for innovation to unlock the silver*. Retrieved from Barrick Web Site: http://www.barrick.com/investors/news/news-details/2007/BarrickOffersUS10MillionforInnovationtoUnlocktheSilver/default.aspx

Barrick. (2017). *Why miners should embrace change*. Retrieved from Barrick Beyond Borders Web Site: http://barrickbeyondborders.com/mining/2017/06/why-miners-should-embrace-change/

BDC. (2017). *Industry 4.0: The new industrial revolution*. Retrieved from Business Development Canada Web Site: https://www.bdc.ca/EN/Documents/analysis_research/bdc-etude-manufacturing-en.pdf?utm_campaign=manufacturing-2017--Studies--EN&utm_medium=email&utm_source=Eloqua

Blackberry. (2017). *Innovation: New ideas to products* . Retrieved from Blackberry QNX Web site: http://www.qnx.com/content/qnx/en/blackberry-qnx-autonomous-vehicle-innovation-centre.html

BP. (2016a). *Artificial intelligence: Turning fantasy into reality*. Retrieved from British Petroleum Web Site: http://www.bp.com/en/global/corporate/bp-magazine/innovations/artificial-intelligence-in-the-energy-industry.html

BP. (2017). *BP energy outlook*. Retrieved from British Petroleum Web Site: https://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2017/bp-energy-outlook-2017.pdf

BP. (2014). *Drones provide BP with eyes in the skies*. Retrieved from British Petroleum Web Site: http://www.bp.com/en/global/corporate/bp-magazine/innovations/drones-provide-bp-eyes-in-the-skies.html

BP. (2016b). *How a new robot fleet is monitoing the underwater world*. Retrieved from British Petroleum Web Site: http://www.bp.com/en/global/corporate/bp-magazine/innovations/ocean-monitoring-with-robot-technology.html

Bresciani, G., Inia, D., & Lambert, P. (2014). *Capturing value in global gas: Prepare now for an uncertain future*. Retrieved from McKinsey & Company Web Site: https://www.mckinsey.com/industries/oil-and-gas/our-insights/capturing-value-in-global-gas

Brooks, R. (2017). *The seven deadly sins of AI predictions*. Retrieved from MIT Technology Review Web Site: https://www.technologyreview.com/s/609048/the-seven-deadly-sins-of-ai-predictions/

Brownlee, J. (2016). *Canada as a global mining leader: With the current downturn, now is the time for the industry to innovate*. Retrieved from Energywise Web Site: http://exportwise.ca/canada-global-mining-leader-now-time-industry-innovate/

BusinessWire. (2017). *Orebits & Symbiont deploy distributed ledger technology to digitize gold ownership*. Retrieved from BusinessWire Web Site:

http://www.businesswire.com/news/home/20170315005332/en/Orebits-Symbiont-Deploy-Distributed-Ledger-Technology-Digitize

CAPP. (2016). *CAPP comments on the Frontier and Offshore Regulatory Renewal Initiative's (FORRI) proposed policy intentions for phase 1 of the framework regulations*. Retrieved from Natural Resource Canada Web Site: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/CAPP_Comments_on_FORRI_Phase1.pdf

CAPP. (2017a). *Industry across Canada*. Retrieved from Canadian Association of Petroleum Producers Web Site: http://www.capp.ca/canadian-oil-and-natural-gas/industry-across-canada

CAPP. (2017b). *Labour*. Retrieved from Canadian Associate of Petroleum Producers Web Site: http://www.capp.ca/canadian-oil-and-natural-gas/economic-competitiveness/labour

Caterpillar. (2017). *Automation keeping underground workers safe at LKAB Malmberget mine*. Retrieved from Caterpillar Web Site: http://www.cat.com/en_US/by-industry/mining/articles/automation-keeps-workers-safe.html

C-CORE. (2007). *ORICA & C-CORE: Aiding automation down under*. Retrieved from C-CORE Web Site: https://www.c-core.ca/cms_content/files/files/C-CORE%20News%20Vol30%20No2%20(Winter%202007).pdf

CDO. (2014). *Creating digitial opportunity - Goal and project description*. Retrieved from Munk School of Global Affairs Web Site: http://munkschool.utoronto.ca/ipl/files/2014/08/CDO_Project-Description.pdf

CERI. (2017). *Ecomonic impacts of Canadian oil and gas supply in Canada and the US (2017-2027)*. Retrieved from Canadian Energy Research Institute Web Site: http://resources.ceri.ca/PDF/Pubs/Studies/Study_166_Full_Report.pdf

Chevron. (2017). *Automation ensuring safe and reliable operations*. Retrieved from Chevron Web Site: https://www.chevron.com/technology/managing-our-assets

Choudhry, H., Mohammad, A., Tan, K. T., & Ward, R. (2016). *The next frontier for digital technologies in oil and gas*. Retrieved from McKinsey & Company Web Site: http://www.mckinsey.com/industries/oil-and-gas/our-insights/the-next-frontier-for-digital-technologies-in-oil-and-gas

Chrisafis, A., & Vaughan , A. (2017). *France to ban sales of petrol and diesel cars by 2040*. Retrieved from The Guardian Web Site: https://www.theguardian.com/business/2017/jul/06/france-ban-petrol-diesel-cars-2040-emmanuel-macron-volvo

CIOPI. (2006). *Centre for Integrated Operations in the Petroleum Industry*. Retrieved from IO Center Web Site: http://www.iocenter.no

CMIC. (2017b). *CLEER: Powering clean growth through mining innovation*. Retrieved from Canada Mining Innovation Council Web Site: http://cmic-ccim.org/powering-clean-growth-mining-innovation/

CMIC. (2017a). *Hackmining*. Retrieved from Canadian Mining Innovation Council Web Site: http://hackmining.cmic-ccim.org

Condliffe, J. (2016). *Humans will bully mild-mannered autonomous cars*. Retrieved from MIT Technology Review Web Site: https://www.technologyreview.com/s/602786/humans-will-bully-mild-mannered-autonomous-cars/

Constas, J. (2017). *The second wave of innovation in the oil patch*. Retrieved from Oil & Gas Financial Journal: http://www.ogfj.com/articles/print/volume-14/issue-3/features/exciting-times-in-oilfield-technology.html

Cook, L., & Cherney, E. (2017). *Get ready for peak oil demand*. Retrieved from Wall Street Journal Web Site: https://www.wsj.com/articles/get-ready-for-peak-oil-demand-1495419061

Cosbey, A., Mann, H., Maennling, N., Toledano, P., Geipel, J., & Brauch, M. D. (2016). *Mining a mirage ?* Retrieved from International Institute for Sustainable Development Web Site: https://www.iisd.org/sites/default/files/publications/mining-a-mirage.pdf

DARPA. (2014). *The DARPA grand challenge: Ten years later*. Retrieved from Defence Advanced Research Projects Agency (DARPA) Web Site: https://www.darpa.mil/news-events/2014-03-13

Davies, A. (2017). *Detroit is stomping Silicon Valley in the self-driving car race.* Retrieved from Wired Web Site: https://www.wired.com/2017/04/detroit-stomping-silicon-valley-self-driving-car-race/

Davis, R. (2017). *Robots and recruitment: The impact of automation on mining jobs*. Retrieved from mining-technology.com Web Site: http://www.mining-technology.com/features/featurerobots-and-recruitment-the-impact-of-automation-on-mining-jobs-5864897/

Deloitte. (2017). *Tracking the trends for 2017*. Retrieved from Deloitte Web Site: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-er-tracking-the-trends-2017.pdf

DNV GL. (2017). *The gas value chain: An energy source for the future*. Retrieved from DNV GL Web Site: https://www.dnvgl.com/oilgas/natural-gas/gas-energy-of-the-future.html

DOE. (2016). *Cadmium-tellurium solar cells: Formula optimized*. Retrieved from Science Daily Web Site: https://www.sciencedaily.com/releases/2016/08/160803151207.htm

Draupner. (2017). *Draupner Energy: About us*. Retrieved from Draupner Energy Web Site: http://draupnerenergy.com

Durrant-Whyte, H., Geraghty, R., Pujol, F., & Sellschop, R. (2015). *How digitial innovation can improve mining productivity*. Retrieved from McKinsey & Company Web Site: http://www.mckinsey.com/industries/metals-and-mining/our-insights/how-digital-innovation-can-improve-mining-productivity

EIA. (2017). *Crude oil and petroleum products explained: Use of oil*. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/energyexplained/index.cfm?page=oil_use

Endress, A. (2017a). *Exxon Mobil's Halsey: Oil patch's digital transformation will be comparable to horizontal drilling's tech revolution.* Retrieved from World Oil Web Site: http://www.worldoil.com/blog/2017/05/15/exxon-mobil-s-halsey-oil-patch-s-digital-transformation-will-be-comparable-to-horizontal-drilling-s-tech-revolution

Endress, A. (2017b). *Oil and gas industry lags new trend of chief digital officers.* Retrieved from World Oil Web Site: http://www.worldoil.com/blog/2017/06/27/oil-and-gas-industry-lags-new-trend-of-chief-digital-officers

ERCB. (2012). *Regulating unconventional oil and gas in Alberta: A discussion paper*. Retrieved from Alberta Energy Regulator Web Site: http://www.aer.ca/documents/projects/URF/URF_DiscussionPaper_20121217.pdf

ExxonMobil. (2016). *A collaboration in curiosity: ExxonMobil and MIT explore the oceans*. Retrieved from ExxonMobil Web Site: https://energyfactor.exxonmobil.com/news/mit-collaboration/

ExxonMobil. (2017). *Outlook for energy: Journey to 2040*. Retrieved from ExxonMobil Web Site: http://corporate.exxonmobil.com/en/energy/energy-outlook/highlights/

EY. (2015a). *Alberta's oil and gas sector regulatory paradigm shift: Challenges and opportunities*. Retrieved from EY Web Site: http://www.ey.com/Publication/vwLUAssets/EY-Alberta-oil-gas-regulatory-paradigm-shift/$FILE/EY-Alberta-oil-gas-regulatory-paradigm-shift.pdf

EY. (2015b). *Driving operational performance in oil and gas*. Retrieved from EY Web Site: http://www.ey.com/gl/en/industries/oil---gas/ey-driving-operational-performance-in-oil-and-gas-1-low-oil-price-highlights-the-need-for-operational-excellence

EY. (2017b). *Productivity in mining: Now comes the hard part*. Retrieved from EY Web Site: http://www.ey.com/Publication/vwLUAssets/EY-productivity-in-mining-now-comes-the-hard-part/$FILE/EY-productivity-in-mining-now-comes-the-hard-part.pdf

EY. (2017a). *The digital disconnect: Problem or pathway*. Retrieved from EY Web Site: http://www.ey.com/Publication/vwLUAssets/EY-the-digital-disconnect-problem-or-pathway/$FILE/EY-digital-disconnect-in-mining-and-metals.pdf

EY. (2016). *Why it's time to invest in digital oil*. Retrieved from EY Web Site: http://www.ey.com/us/en/industries/oil---gas/ey-why-the-time-is-right-for-digital-oil-companies

Farah, A. (2016). *Cost-cutting not enough to hit IOC growth target*. Retrieved from Oil & Gas Journal Web Site: http://www.ogj.com/articles/print/volume-114/issue-8/drilling-and-processing/cost-cutting-not-enough-to-hit-ioc-growth-target.html

Fattoch, B. (2016). *Adjustment in the oil market: Structural, cyclical or both ?* Retrieved from Oxford Institute for Energy Studies Web Site: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2016/05/Adjustment-in-the-Oil-Market-Structural-Cyclical-or-Both.pdf

Ford, J., Steen, J., & Verreynne, M.-L. (2014). *How environmental regulations affect innovation in the Australian oil and gas industry: going beyond the Porter Hypothesis*. Retrieved from Journal of Cleaner Production (Elsevier) Web Site: https://doi.org/10.1016/j.jclepro.2013.12.062

FP. (2015). *Canadian miner offers $1 million to anyone who can strike gold in six terabytes of data*. Retrieved from Financial Post Web Site: http://business.financialpost.com/commodities/mining/canadian-miner-offers-1-million-to-anyone-who-can-strike-gold-in-six-terabytes-of-data

Geissbauer, R., Vedso, J., & Schrauf, S. (2016). *Industry 4.0: Building the digitial enterprise*. Retrieved from PricewaterhouseCoopers Web Site: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf

Gershgom, D. (2016). *Self-driving 416-ton trucks are hauling raw materials around Australia*. Retrieved from Quartz Web Site: https://qz.com/874589/rio-tinto-is-using-self-driving-416-ton-trucks-to-haul-raw-materials-around-australia/

GE-Statoil. (2015). *GE AND Statoil collaboration announces winners of inaugural open innovation challenge*. Retrieved from General Electric Web Site:

http://www.genewsroom.com/press-releases/ge-and-statoil-collaboration-announces-winners-inaugural-open-innovation-challenge

Global Economics. (2001). *Mining innovation: An overview of Canada's dynamic, technologically advanced mining industry*. Retrieved from Global Economics Limited Web Site: http://global-economics.ca/mining_innovation.pdf

Gonzalez, C. (2016). *Advanced robotic systems: The manufacturing labor force of tomorrow*. Retrieved from Machine Design Web Site: http://www.machinedesign.com/robotics/advanced-robotic-systems-manufacturing-labor-force-tomorrow

Gosine, R., Dusseault, M., Gagnon, G., Keough, K., & Locke, W. (2016). *Unconventional opportunites and challenges: Results of the public review of the implications of hydraulic fracturing operations in Western Newfoundland*. Retrieved from Newfoundland and Labrador Hydraulic Fracturing Review Panel Web Site: http://nlhfrp.ca

Grant, T. (2015, July 26). *Driverless trucks could mean 'game over' for thousands of jobs*. Retrieved from Globe and Mail Web Site: https://beta.theglobeandmail.com/report-on-business/autonomous-trucks-could-transform-labour-market-eliminate-driver-jobs/article25715184/?ref=http://www.theglobeandmail.com&

Guillen, M. (2017). *Five ways technology will change the mining, oil and gas industries*. Retrieved from World Economic Forum Web Site: https://www.weforum.org/agenda/2017/05/five-ways-in-which-technology-will-change-the-extractive-industries/

Hacking Health. (2017). *Hacking Health*. Retrieved from Hacking Health Web Site: http://hacking-health.org

Hall, H. (2017). *Exploring innovation in Northern Canada with insights from the mining innovation system in Greater Sudbury, Ontario* . Retrieved from The Northern Review Web Site: http://journals.sfu.ca/nr/index.php/nr/article/view/660/674

Hebron. (2008). *Hebron benefits agreement*. Retrieved from Hebron Project Web Site: http://www.hebronproject.com/docs/benefits/finalexecutedbenefits.pdf

HMDC. (2017). *Hibernia Management and Development Company Ltd. Canada – Newfoundland and Labrador Benefits Report April 1st – June 30th, 2017*. Retrieved from Hibernia Management and Development Company Web Site: http://www.hibernia.ca/Q2Benefits2017.pdf

Hollinger, P. (2016). *Meet the cobots: Humans and robots together on the factory floor*. Retrieved from Financial Times Web Site: https://www.ft.com/content/6d5d609e-02e2-11e6-af1d-c47326021344

Husky. (2017). *Husky Energy - Operations/Atlantic* . Retrieved from Husky Energy Web Site: http://www.huskyenergy.ca/operations/atlantic.asp

IBA RN. (2006). *Impacts and benefits agreements: Background*. Retrieved from IBA Research Network Web Site: http://www.impactandbenefit.com

IBM. (2016). *Trust in trade: Toward strong supply chains*. Retrieved from IBM Institute for Business Value Web Site: https://public.dhe.ibm.com/common/ssi/ecm/gb/en/gbe03771usen/GBE03771USEN.P DF

ICICS. (2010). *ICICS-incubated start-up company an international success*. Retrieved from UBC Library Web Site: https://open.library.ubc.ca/media/download/pdf/focus/1.0115147/0

ideaconnection. (2009). *Open innovation: Goldcorp challenge*. Retrieved from ideaconnection Web Site: https://www.ideaconnection.com/open-innovation-success/Open-Innovation-Goldcorp-Challenge-00031.html

IFR. (2017). *The impact of robotics on productivity, employment and jobs*. Retrieved from International Federation of Robotics Web Site: https://ifr.org/img/office/IFR_The_Impact_of_Robots_on_Employment.pdf

IFR. (2016). *US-Industry: 135,000 new robots bring jobs back home*. Retrieved from International Federation of Robotics Web Site: https://ifr.org/ifr-press-releases/news/us-industry-135000-new-robots-bring-jobs-back-home

Inco. (1998). *Starting the process to complete remote mining (unpublished report).* Inco Limited and partners.

InfoMine. (2017). *Commodity and metals prices*. Retrieved from InvestmentMine Web Site: http://www.infomine.com/investment/metal-prices/

ISA. (2017). *International Seabed Authority*. Retrieved from International Seabed Authority Web Site: https://www.isa.org.jm

ISI. (2017). *Innovation superclusters initiative (ISI): Program guide*. Retrieved from Government of Canada Web Site: https://www.ic.gc.ca/eic/site/093.nsf/eng/00003.html#toc-01.01

Ivey. (2016). *Energy in Canada: A statistical overview*. Retrieved from Ivey Business School Web Site: https://www.ivey.uwo.ca/cmsmedia/2110828/energy-in-canada-a-statistical-overview.pdf

Jacquand, R. (2017). *Us and them*. Retrieved from Mining Magazing Web Site: http://www.miningmagazine.com/opinion/industry-comment/us-and-them/

Jamasmie, C. (2017). *Copper to be the best performing commodity of 2017 - analysts*. Retrieved from Mining.com Web Site: http://www.mining.com/copper-best-performing-commodity-2017-analysts/

Jarvis, C. (2016). *Innovation is a social process - which means collaboration is key*. Retrieved from Virgin Web Site: https://www.virgin.com/entrepreneur/innovation-social-process-which-means-collaboration-key

Jensen, S. (2016). *The growing potential for fully autonomous mines*. Retrieved from OEM Off-Highway Web Site: http://www.oemoffhighway.com/electronics/smart-systems/automated-systems/article/12243110/autonomous-mining-equipment

Kielland, N. (2015). *Supporting Aboriginal participation in resource development: The role of impact and benefits agreements*. Retrieved from Library of Parliament Web Site: https://lop.parl.ca/content/lop/ResearchPublications/2015-29-e.pdf

Kline, C. (2017). *Digital transformation in oil & gas: Transforming the experience*. Retrieved from PennEnergy Web Site: http://www.pennenergy.com/articles/pennenergy/2017/04/digital-transformation-in-oil-gas-transforming-the-experience.html

Koeppen, M., Shrier, D., & Bazilian, M. (2017). *Is blockchain's future in oil and gas transformative or transient ?* Retrieved from Deloitte Web Site: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-blockchain-report.PDF

Koven, P. (2014). *In risk-averse mining sector, innovation begins with taking the guesswork out of sorting rock*. Retrieved from Financial Post Web Site: http://business.financialpost.com/executive/smart-shift/in-risk-averse-mining-sector-innovation-begins-with-taking-the-guesswork-out-of-sorting-rock

Latimer, C. (2015). *Rio calls for focus on social licence to operate*. Retrieved from Australian Mining Web Site: https://www.australianmining.com.au/news/rio-calls-for-focus-on-social-licence-to-operate/

Leber, J. (2012). *Big oil goes mining for big data*. Retrieved from MIT Technology Review Web Site: https://www.technologyreview.com/s/427876/big-oil-goes-mining-for-big-data/

Lindeman, T. (2015). *Hacking Health drives healthcare into the 21st century with new accelerator*. Retrieved from Montreal Gazette Web Site: http://montrealgazette.com/business/hacking-health-drives-healthcare-into-21st-century-with-new-accelerator

LR. (2015a). *Five issues affecting the oil and gas sector: Failure or inability to adopt technology*. Retrieved from Lloyd's Register Web Site: http://www.lr.org/en/news-and-insight/articles/failure-or-inability-to-adopt-technology.aspx

LR. (2015b). *Five issues affecting the oil and gas sector: Regulation and legislation*. Retrieved from Lloyd's Register Web Site: http://www.lr.org/en/news-and-insight/articles/regulation-and-legislation-issues.aspx

LRF. (2014). *Foresight review of big data*. Retrieved from Lloyd's Register Foundation Web Site: http://www.lrfoundation.org.uk/publications/bigdata.aspx

LRF. (2016). *Foresight review of robotics and autonomous systems: Serving a safer world*. Retrieved from Lloyd's Register Foundation Web Site: http://www.lrfoundation.org.uk/news/2016/foresight-review-of-robotics-and-autonomous-systems.aspx

MAC. (2016). *F&F2016 - Facts and figures of the Canadian mining industry*. Retrieved from Mining Association of Canada Web Site: http://mining.ca/sites/default/files/documents/Facts-and-Figures-2016.pdf

Macrotrends. (2017). *Brent crude oil prices - 70 year historical chart*. Retrieved from Macrotrends Web Site: http://www.macrotrends.net/2480/brent-crude-oil-prices-10-year-daily-chart

Mann, H., & Cosbey, A. (2016). *As mines become more automated, what happens to the social licence to operate?* Retrieved from International Institute for Sustainable Development Web Site: https://www.iisd.org/blog/mines-become-more-automated-what-happens-social-licence-operate

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., & Marrs, A. (2013). *Disruptive technologies: Advances that will transform life, business and the global economy*. Retrieved from McKinsey & Company Web Site: http://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/disruptive-technologies

Manyika, J., Chui, M., Miremadi, M., Bughin, J., George, K., Willmott, P., et al. (2017). *A future that works: Automation, employment, and productivity*. Retrieved from McKinsey & Company Web Site: http://www.mckinsey.com/global-themes/digital-disruption/harnessing-automation-for-a-future-that-works

Marshall, A. (2017a). *As Uber flails, its self-driving tech rolls on*. Retrieved from Wired Web Site: https://www.wired.com/story/uber-crisis-self-driving-pittsburgh/

Marshall, A. (2017b). *Volvo's electric car plan isn't as bold or crazy as it seems*. Retrieved from Wired Web Site: https://www.wired.com/story/volvos-electric-car-plan/

Marshall, J., Bonchis, A., Nebot, E., & Scheding, S. (2016). Robotics in Mining. In *Springer Handbook of Robotics.* DOI: 10.1007/978-3-319-32552-1_59.

Matsumoto, A. (2015). *What is affecting metals prices ?* Retrieved from World Economic Forum Web Site: https://www.weforum.org/agenda/2015/09/what-is-affecting-metals-prices/

Maxwell, J. (2003). *Innovation is a social process*. Retrieved from Statistics Canada Web Site: http://www.statcan.gc.ca/pub/88f0006x/88f0006x2003006-eng.pdf

May, M. (2012). *The rules of successful skunk works projects*. Retrieved from Fast Company Web Site: https://www.fastcompany.com/3001702/rules-successful-skunk-works-projects

McKinsey. (2013). *Opportunities for Canadian energy technologies in global markets*. Retrieved from Natural Resources Canada Web Site: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/files/pdf/2013/McK-Report-eng.pdf

McNab, K., Onate, B., Brereton, D., Horberry, T., Lynas, D., & Franks, D. (2013). *Exploring the social dimensions of autonomous and remote operation mining: Applying social licence in design*. Retrieved from The University of Queensland Sustainable Minerals Institute Web Site: https://www.csrm.uq.edu.au/publications/exploring-the-social-dimensions-of-autonomous-and-remote-operation-mining-applying-social-license-in-design

Mining Global. (2014). *Penguin ASI takes mining automation to the next level*. Retrieved from Mining Global Web Site: http://www.miningglobal.com/technology/penguin-asi-takes-mining-automation-next-level

MMI. (2017). *Motion Metrics International Corporation* . Retrieved from Motion Metrics International (MMI) Web Site: http://www.motionmetrics.com/about/

MNP. (2011). *Regulatory barrier identification and analysis - Green mining*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/mineralsmetals/files/pdf/pub-pub/reg-reg-eng.pdf

Moren, D. (2017). *Apple's drive toward an autonomous car*. Retrieved from Macworld Web Site: https://www.macworld.com/article/3201051/car-tech/apples-drive-towards-an-autonomous-car.html

Musk, E. (2013). *Hyperloop alpha*. Retrieved from SpaceX Web Site: http://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf

NASA. (2017). *NASA's robotic mining competition*. Retrieved from Kennedy Space Center Web Site: https://www.kennedyspacecenter.com/events/events-calendar/2017/may/event-nasas-robotic-mining-competition

New Scientist. (1975). *Exxon sinks its oil production (New Scientist, February 6, 1975)*. Retrieved from Google Books Web Site: https://books.google.ca/books?id=pnV6UYEkU4YC&pg=PA317&lpg=PA317&dq=remote+drilling+exxon&source=bl&ots=m5rB5nZzIS&sig=yLVht6XjU7X1H1mqHbzInSQHQkE&hl=en&sa=X&ved=0ahUKEwjWh_mn6ITWAhWLz4MKHVq7BlsQ6AEIYTAJ#v=onepage&q&f=false

NRCan. (2017a). *10 key facts on Canada's natural resources*. Retrieved from Natural Resources Canada Web Site: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/files/pdf/10_key_facts_nrcan_2017_en.pdf

NRCan. (2017b). *Canadian mineral production: Information bulletin, March 2017*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/mining-materials/publications/17722#table1

NRCan. (2017c). *Energy sources and distribution*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/energy/energy-sources-distribution

NRCan. (2017d). *Frontier and offshore regulator renewal initiative*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/energy/crude-petroleum/17729

NRCan. (2013). *Literature review to assess the relevance of outcome-based regulations to innovation*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/mining-materials/publications/11732#e0

NRCan. (2016). *Rare earth elements (REE) and chromite*. Retrieved from Natural Reseources Canada Web Site: http://www.nrcan.gc.ca/mining-materials/green-mining/18274

NRCan. (1996). *The minerals and metals policy of the Government of Canada*. Retrieved from Natural Resources Canada Web Site: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/mineralsmetals/pdf/mms-smm/poli-poli/pdf/mmp-eng.pdf

NTNU. (2017). *NTNU oceans pilot on deep sea mining*. Retrieved from NTNU Web Site: https://www.ntnu.edu/oceans/deep-sea-mining#Environmental%20aspects%20of%20deep%20sea%20mining

OGA. (2016). *Hackathon identifies more than 60 ideas to transform well construction on UKCS*. Retrieved from UK Oil and Gas Authority Web Site:

https://www.ogauthority.co.uk/news-publications/news/2016/hackathon-identifies-more-than-60-ideas-to-transform-well-construction-on-ukcs/

Perrons, R. (2010). *Perdido ties together Shell digital oilfield technologies* . Retrieved from World Oil Web Site: http://www.worldoil.com/magazine/2010/may-2010/features/perdido-ties-together-shell-digital-oilfield-technologies

Phillips, P., & Wixted, B. (2017). *Differential adoption of digital technology in the Canadian agriculture and mining sectors*. Retrieved from Munk School of Global Affairs Web Site: http://munkschool.utoronto.ca/ipl/files/2017/05/PhillipsP-Sess5-Day3-Presentation.pdf

PRNL. (2017). *Integrated operations*. Retrieved from Petroleum Research Newfoundland and Labrador Web Site: http://petroleumresearch.ca/index.php?id=176

PwC. (2016a). *Not your father's oil and gas business: Reshaping the future with upstream digitization*. Retrieved from PricewaterhouseCooper Web Site: https://www.strategyand.pwc.com/media/file/Not-your-fathers-oil-and-gas-business.pdf

PwC. (2016b). *Unrealized potential of digital*. Retrieved from PricewaterhouseCooper (PwC) Web Site: https://www.pwc.com/us/en/energy-mining/publications/assets/pwc-unrealized-potential-of-digital.pdf

Rapier, R. (2017). *Peak oil and peak demand have entirely different outcomes*. Retrieved from Forbes Web Site: https://www.forbes.com/sites/rrapier/2017/08/15/peak-oil-and-peak-demand-have-entirely-different-outcomes/#a7d75bf74f01

Ratzesberger, O. (2015). *Hacking IoT: Fast-tracking transformational IoT solutions*. Retrieved from Teradata Web Site: http://bigdata.teradata.com/US/Articles-News/Hacking-IoT--Fast-Tracking-Transformational-IoT-Solutions/

ResearchInfosource. (2017). *Aquaculture and energy firms team up to bid for oceans supercluster in Atlantic Canada*. Retrieved from ResearchInfosource Web Site: https://researchmoneyinc.com

ResearchInfosource. (2010). *Canada's top 100 corporate R&D spenders 2010*. Retrieved from ResearchInfosource Web Site: https://researchinfosource.com/pdf/2010-top100-sup.pdf

ResearchInfosource. (2017a). *Canada's top 100 corporate R&D spenders list 2016*. Retrieved from ResearchInfosource Web Site: https://researchinfosource.com/top100_corp.php

RIA. (2017). *Robots in the oil and gas industry*. Retrieved from Robotic Industry Association Web Site: https://www.robotics.org/blog-article.cfm/Robots-in-the-Oil-and-Gas-Industry/40

Roscoe, A. (2015). *The digital future of corporate responsibility*. Retrieved from Stanford Social Innovation Review Web Site: https://ssir.org/articles/entry/the_digital_future_of_corporate_responsibility

Sandvik. (2017). *Equipment automation and teleoperation systems*. Retrieved from Sandvik Web Site: https://mining.sandvik.com/en/products/equipment/mine-automation-systems/equipment-automation

Sanyal, D. (2012). *Obtaining a social licence to operate – A challenge for the industry*. Retrieved from British Petroleum Web Site: http://www.bp.com/en/global/corporate/media/speeches/obtaining-social-license-to-operate.html

Schlumberger. (2016). *Schlumberger robotics services*. Retrieved from Schlumberger Web Site: http://www.slb.com/services/additional/robotics-services.aspx

Schwab, K. (2016). *The fourth industrial revolution: What it means, how to respond*. Retrieved from World Economic Forum Web Site: https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/

Shell. (2017a). *Digitial innovaton*. Retrieved from Shell Web Site: http://www.shell.com/energy-and-innovation/overcoming-technology-challenges/digital-innovation.html

Shell. (2017b). *Unlocking oil and gas*. Retrieved from Shell Web Site: http://www.shell.com/energy-and-innovation/overcoming-technology-challenges/unlocking-oil-and-gas.html

Shukman, D. (2017). *Renewables' deep-sea mining conundrum*. Retrieved from BBC Web Site: http://www.bbc.com/news/science-environment-39347620

Simonite, T. (2016). *Mining 24 hours a day with robots* . Retrieved from MIT Technology Review Magazine Web Site: https://www.technologyreview.com/s/603170/mining-24-hours-a-day-with-robots/

Sloman, C., Holsman, R., & Cantrell, S. (2014). *The future of work in the oil and gas industry*. Retrieved from Accenture Web Site: https://www.accenture.com/t20150523T022425__w__/us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Dualpub_1/Accenture-Digitizing-Energy-Future-Work-Oil-Gas-Industry.pdf

Smith, K., Dietrichs, E., & Nas, S. O. (2015). *The Norwegian National Innovation System: A preliminary overview and assessment*. Retrieved from Organization for Economic Co-operation and Development Web Site: http://www.oecd.org/sti/inno/2373824.pdf

SpaceX. (2017). *2018 SpaceX hyperloop pod competition* . Retrieved from SpaceX Web Site: http://www.spacex.com/sites/spacex/files/2018_hyperloop_competition_rules.pdf

Statistics Canada. (2017a). *Gross domestic product at basic prices, by industry (monthly)*. Retrieved from Statistics Canada Web Site: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/gdps04a-eng.htm

Statistics Canada. (2017b). *Labour force survey estimates (LFS), by North American Industry Classification System (NAICS), sex and age group*. Retrieved from Statistics Canada Web Site: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=2820008&&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid=

Statoil. (2017a). *Digitalisation driving value creation*. Retrieved from Statoil Web Site: https://www.statoil.com/en/news/digitalisation-driving-value-creation.html

Statoil. (2017c). *Statoil innovate*. Retrieved from Statoil Web Site: https://www.statoil.com/en/how-and-why/innovate.html

Statoil. (2017b). *Where are we - Canada*. Retrieved from Statoil Web Site: https://www.statoil.com/en/where-we-are/canada.html

Statoil-GE. (2016). *GE and Statoil announce winners of open innovation challenge*. Retrieved from Statoil Web Site: https://www.statoil.com/en/news/winners-innovation-challenge.html

Steen, J., Macaulay, S., Kunz, N., & Jackson, J. (2017). Understanding the innovation ecosystem in mining and what the digital revolution means for it. In *Extracting Innovations: Mining, Energy, and Technological Change in the Digital Age (to appear)*.

Sussex. (2017). *Automation anxiety*. Retrieved from Automation Anxiety AHRC Network Web Site: http://blogs.sussex.ac.uk/automationanxiety/

Tertzakian, P. (2017b). *Commentary - How EVs jolt the oil business*. Retrieved from ARC Energy Research Institute Web Site: https://www.arcenergyinstitute.com/commentary-how-evs-jolt-the-oil-business/

Tertzakian, P. (2017a). *Commentary – Why ban the engine ?* Retrieved from ARC Energy Research Institute Web Site: https://www.arcenergyinstitute.com/commentary-why-ban-the-engine/

Tesla. (2016). *All Tesla cars being produced now have full self-driving hardware.* Retrieved from Tesla Web Site: https://www.tesla.com/en_CA/blog/all-tesla-cars-being-produced-now-have-full-self-driving-hardware

The Scientist. (1987). *Canadian consortium formed (Novemeber 1987 issue)*. Retrieved from The Scientist Web Site: http://www.the-scientist.com/?articles.view/articleNo/9078/title/Canadian-Consortium-Formed/

Ticoll, D. (2017). *Jobs impact of automation: Bigger than the thought leaders say it is*. Retrieved from Munk School of Global Affairs Web Site: http://munkschool.utoronto.ca/ipl/files/2017/05/Ticoll-Sess3-Day2-Presentation1-1-1.pdf

Tischler, L. (2002). *He struck gold on the net (really)* . Retrieved from Fast Company Web Site: https://www.fastcompany.com/44917/he-struck-gold-net-really

Tobe, F. (2015). *Why co-bots will be a huge innovation and growth driver for robotics industry*. Retrieved from IEEE Spectrum Web Site: https://spectrum.ieee.org/automaton/robotics/industrial-robots/collaborative-robots-innovation-growth-driver

Topf, A. (2016). *Canadian oil sands giant testing autonomous haul trucks*. Retrieved from Mining.com Web Site: http://www.mining.com/canadian-oil-sands-giant-testing-autonomous-haul-trucks/

Torres, N. (2016). *The Petrobot project: Chevron field tests tank inspection robots*. Retrieved from Petro Global News Web Site: https://petroglobalnews.com/2016/09/the-petrobot-project-chevron-field-tests-tank-inspection-robots/

UK. (2017). *Plan for roadside NO2 concentration published*. Retrieved from Government of United Kingdom Web Site: https://www.gov.uk/government/news/plan-for-roadside-no2-concentrations-published

Unearthed. (2017). *Vancouver 2017*. Retrieved from Unearthed Solutions Web Site: https://unearthed.solutions/hackathons/unearthed-vancouver-2017/

Vale. (2017). *Impacts and benefits agreements*. Retrieved from Vale Web Site: http://www.vale.com/canada/EN/business/mining/nickel/vale-canada/voiseys-bay/Pages/Impacts-and-Benefits-Agreements.aspx

Vella, H. (2016). *Can fully-automated drilling technology finally win over the offshore oil industry?* Retrieved from offshore-technology Web Site: http://www.offshore-technology.com/features/featurecan-fully-automated-drilling-technology-finally-win-over-the-offshore-oil-industry-4912630/

Vella, H. (2017). *Ultra-deep mining - Overcoming challenges with industry collaboration*. Retrieved from mining-technology.com Web Site: http://www.mining-technology.com/features/featureultra-deep-mining-overcoming-challenges-with-industry-collaboration-4210176/

Ward, R. (2016). *A billion-dollar digitial opportunity for oil companies*. Retrieved from McKinsey & Company Web Site: http://www.mckinsey.com/industries/oil-and-gas/our-insights/a-billion-dollar-digital-opportunity-for-oil-companies

Watkins, C. (2017). *Caterpillar offers stepping stones to full automation.* Retrieved from Canadian Mining Journal Web Site: http://www.canadianminingjournal.com/features/caterpillar-offers-stepping-stones-full-automation/

Werniuk, J. (2001). *Staying on top of underground mining*. Retrieved from Canadian Mining Journal Web Site: http://www.canadianminingjournal.com/features/staying-on-top-of-underground-mining/

World Atlas. (2017). *Deepest mines in the world*. Retrieved from World Atlas Web Site: http://www.worldatlas.com/articles/the-deepest-mines-in-the-world.html

Yeates, G. (2017). *The mining industry disrupted*. Retrieved from The AUSImm Bulletin Web Site: https://www.ausimmbulletin.com/feature/mining-industry-disrupted/