Mining, Metallurgy & Exploration (2026) 43:3081–3102
https://doi.org/10.1007/s42461-026-01545-9

Eliminating Barriers for the Implementation of Automation in the Mining Industry

Sefiu O. Adewuyi[1] · Kray Luxbacher[1] · Kanagy David[2] · Miller Ben[3] · Miller Hugh[4] · Moats Michael[5] · Savit Mark[6]

Received: 3 November 2025 / Accepted: 18 March 2026 / Published online: 30 March 2026

Abstract
The integration of new technologies into U.S. mining operations is necessary for achieving continuous improvement in worker health and safety, as well as improving operational efficiency, but many have questioned why uptake of autonomy in the U.S. mining industry has been slow compared to other nations. Despite extensive research on mining automation, there remains a critical gap in understanding and systematically identifying the barriers to its adoption within the U.S. mining industry and globally. To quantify these barriers, a workshop model of data collection was employed. A total of 708 invitations were extended to professionals to participate in nine different workshops between 2022 and 2024, representing 480 companies, with a total of 146 participants. In addition, online virtual meetings were held with leadership of the U.S. Mine Safety and Health Administration (MSHA), National Institute of Occupational Safety and Health (NIOSH), Society of Mining, Metallurgy and Exploration (SME) and academia, with a total of about 139 participants. Participants categorize major barriers to mining automation into regulation, economics, technology readiness, corporate willingness, and social license. The weighted average of the ranks of these barriers indicates that economics, technology readiness, and regulation are the three most significant barriers to mining automation, contributing 37.9%, 17.4%, and 16.6%, respectively. While the first two significant barriers may be handled by the private sector, removing the regulatory barrier requires government collaboration. The review of the regulation reveals that there are approximately 98 regulations identified as presenting potential barriers to automation or innovation in the U.S. mining industry.

Keywords Equipment Autonomy · Sensors · Artificial Intelligence · Communication · Mining Automation

1 Introduction

The mining industry has undergone a significant technological transformation, from the early reliance on manual hand tools to the adoption of continuous miners, remote-controlled systems, and automated load-haul-dump (LHD) equipment (Fig. 1). This evolution has culminated in the deployment of autonomous machines and digital systems, marking a transition into the era of Industry 4.0, where real-time data analytics, and automation are reshaping mining operations for enhanced efficiency, safety, and sustainability [1]. The transformation was driven by a desire to resolve challenges with existing technology for improved production, mineral recovery, economics, and most importantly workers' health and safety [2]. These are considerable incentives and quality gains related to mining automation; however, they are often eroded by perceived and actual barriers that impair or restrict the implementation of these technologies by the mining industry. The challenges associated

✉ Sefiu O. Adewuyi
sadewuyi@arizona.edu

✉ Kray Luxbacher
kraylux@arizona.edu

1 School of Mining Engineering and Mineral Resources, The University of Arizona, Tucson, AZ 85721, USA

2 Society of Mining, Metallurgy, and Exploration, 12999 E Adam Aircraft CIR Englewood, Englewood, CO 90112-4167, USA

3 Lewicki and Associates, Littleton, CO 80123, USA

4 Department of Mining Engineering, Colorado School of Mines, Golden, CO 80401, USA

5 Department of Materials Science and Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA

6 MSHAWise LLC, Denver, CO 80202, USA

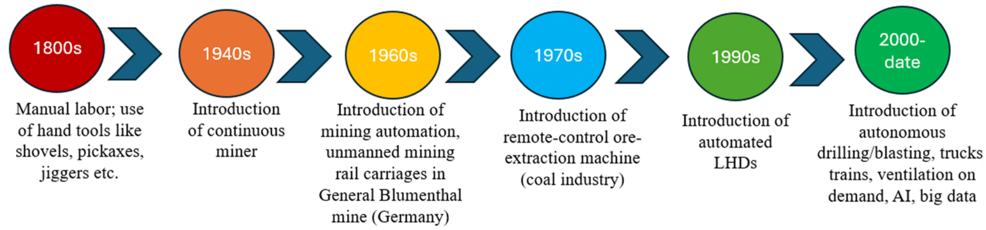

Fig. 1 Developmental stages of mining mechanization and automation (information extracted from [3, 4])

with deploying autonomous equipment in the mining industry were first identified nearly five decades ago, when such technologies faced significant limitations due to the harsh and unpredictable conditions of mining environments [2]. As these challenges were addressed, autonomous equipment is more complex and comprises systems (e.g., full haulage fleets) that rely extensively on specialized skills required for a new workforce.

Due to safety concerns and economic implications of introducing new technology into existing operations, the mining industry is in many cases reluctant to adopt new innovative technology, as compared to other industries such as computing and manufacturing. In particular, the additional financial risk associated with disruption to production is a disincentive. Bellamy and Pravica [3] are of the view that this reluctance may be attributed to length of time required to develop new technology for the mining industry, which may not be in line with the company's short-term plan. The time for new technology to reach the commercialization stage is approximately 10 years, which makes it difficult to deploy in existing mines that have developed specialized mine plans around equipment [3].

For instance, Autonomous Mining Truck System (AMTS) was pioneered in Japan by Caterpillar Japan Co., Ltd. (formerly Shin Caterpillar Mitsubishi Ltd.) around 1993 and field tested at Shuho mine in 1999 but was deployed at mine operations in Japan in 2007 [5]. The AMTS is now referred to as Autonomous Haulage Systems (AHS), and the paradox is that while the mining industry may be slow to embrace new technology, it is also recognized as having pioneered the earliest self-driving vehicles [6, 7]. In the late 1990s, Komatsu commenced the modular mining systems but faced challenges with fleet management. In 2005, Komatsu performed the proof of concept on AHS at Codelco's Gabriela Mistral Mine (Chile) and started commercial operation at the same mine in 2008 [8]. As of 2024, Komatsu has commissioned more than 750 AHS worldwide [9]. Costner [6] and others reported that Caterpillar successfully tested a fleet of autonomous haul trucks at a U.S. surface mine as far back as 2014, showing that these systems were not only reliable but also safe. Today, more than 900 trucks have been deployed globally and are collectively moving more than two billion tons annually with zero lost time accidents [10, 11]. Despite the achievements made so far by Caterpillar and Komatsu in mining automation, there are barriers to the adoption of mining automation in the U.S. mining industry.

The source of these barriers has been a matter of conjecture but likely stems from a variety of sources that vary by industry sector, regulatory and economic considerations. For example, the regulatory standards under which U.S. mines operate are prescriptive in nature as compared to most other countries [12] and were promulgated in an environment in which regulators sought to hold operators liable for absolute control of the mine environment. The authors of the Mine Act [13] and subsequent statutes could not have foreseen the rapid development of technical advances that have occurred in the industry, including the introduction of fully autonomous mining systems. Consequently, the prescriptive regulatory system under which U.S. mines operate often provides little motivation – and at times, creates barriers – to the implementation of new technologies and highly automated systems that could not only achieve superior economic outcomes but also improve both worker safety and health.

Similar barriers exist in the integration of new processes, equipment, and technology in all underground coal and non-coal mines [14], as well as new mines undergoing permitting and financing, where new technology is often perceived to be a contributing factor in greater economic or operational risk. Others have examined specific regulatory standards that govern the use of permissible equipment in the U.S. and have determined that alternatives or additions to the regulations would not reduce the standard of safety provided to miners [15]. This finding supports the use of consensus standards for the permissibility of equipment for use in gassy underground environments, by the Mine Safety and Health Administration (MSHA).

In processing mined ores, the implementation of technologies related to processing automation and control has become prominent throughout the industry. This is particularly evident in the use of distributed computer control systems that leverage innovative sensor technologies to reduce energy consumption and improve process efficiency [16]. Further, automation provides opportunities to isolate workers from potential safety hazards and adverse health exposures (e.g., dust, noise, heat, chemical reagents, and toxic substances). Despite these benefits, some processing facilities have elected not to utilize these technologies [17] for a variety of reasons. Identifying these reasons is a central objective of this research.

To encourage the rapid integration of new technology into U.S. mining operations and to promote worker safety, better resource utilization, and greater economic utility, a comprehensive review and analysis of the regulatory framework and external factors influencing technology integration in mine and plant development and operations is needed in order to characterize the potential barriers that exist and the causation factors that govern why these barriers exist and how they evolve. Additionally, this paper sought to provide an understanding of different regulatory approaches, the political/social risks associated with innovation, and research that could enable high levels of automation in the U.S. mines and processing plants to occur. This part of the analysis also relied on an examination of how technology is adopted in other countries using alternative regulatory structures. This work is a necessary component to eliminate barriers for future technological initiatives in the mining industry [17, 18] with the ultimate goal of increasing worker safety and improving worker health.

2 Current State of Mining Automation: Research Development and Deployment

The international approach to autonomous mining can be most easily observed in AHS because it represents the largest conversion of mining activities to autonomous operations. Bibliographic analysis of the search term “Autonomous Haulage Systems” OR “Autonomous Mining Truck Systems” using Scopus database (27 documents; accessed 7/15/2025) shows that AHS has received considerable attention from researchers in recent years with focus on safety purposes in open pit mining (Fig. 2). Due to the low number of documents found using “Autonomous Haulage Systems” OR “Autonomous Mining Truck Systems”, the search term “mining automation” OR “autonomous mining” was used to acquire a total of 411 documents. As expected, automation of mining operations has received great attention with an increasing trend in research output in recent years, which may be attributed to the growing demand for mining sustainability and resource efficiency (Fig. 3). The most relevant of the 411 documents obtained were downloaded, reviewed and summarized in Table 1. It can be noted that Australia dominated the research on mining automation, which has

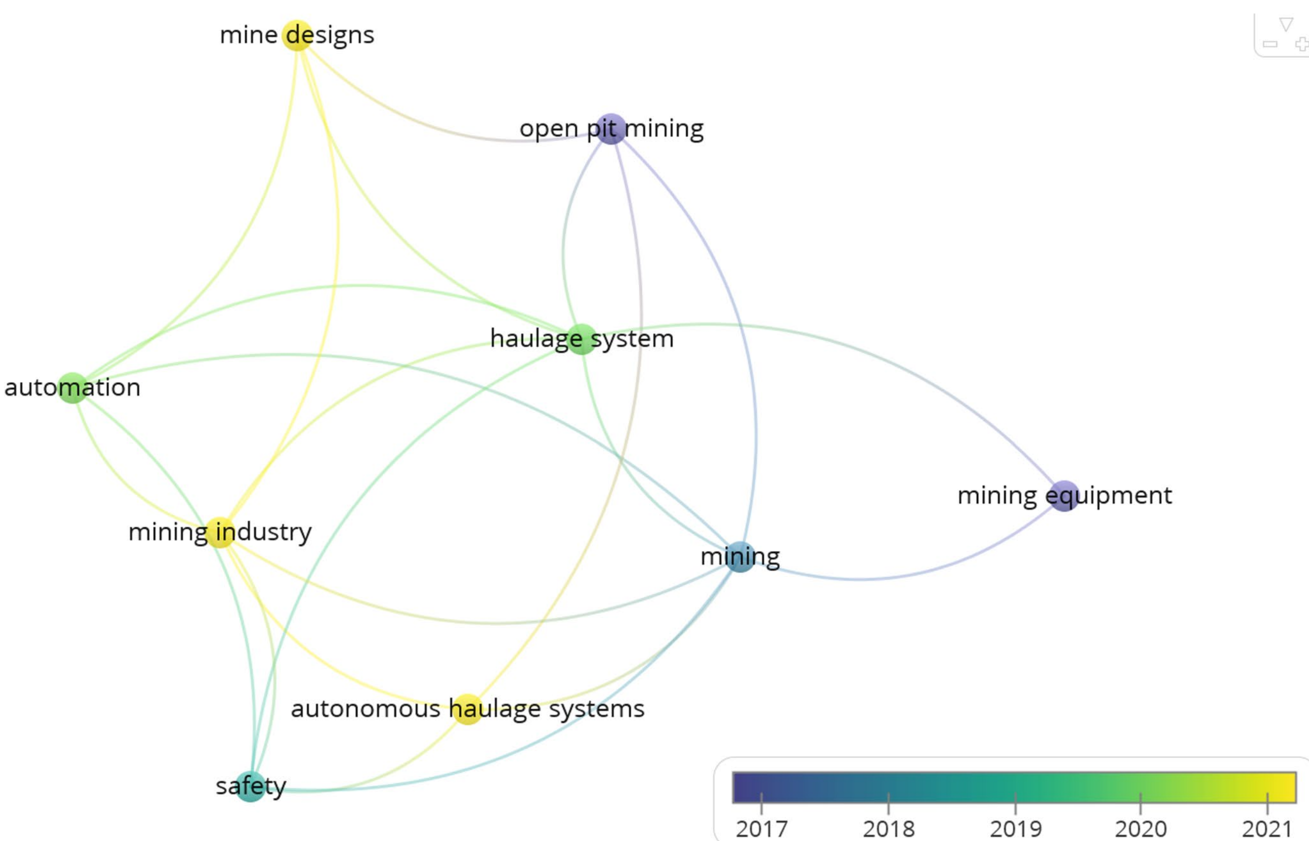

Fig. 2 Bibliographic analysis of the search term “Autonomous Haulage Systems” OR “Autonomous Mining Truck Systems” using Scopus database [19]; generated using open-source software; VOSviewer (version 1.6.19)

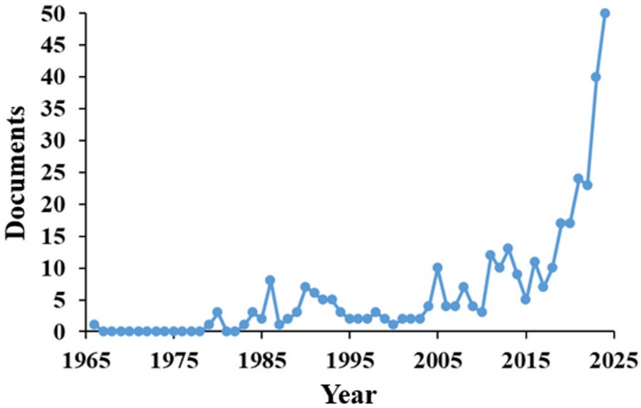

Fig. 3 Document by year on automation research using the search term "mining automation" OR "autonomous mining " (Data extracted from [20])

contributed to significant progress in the deployment of automated equipment in the country. Based on the current research progress (Table 1), there is a significant gap in understanding the barriers to mining automation; this paper fills this gap. Section 3 provides the methodology employed for data acquisition, while barriers and drivers to mining automation in the U.S. are presented in Sect. 4.

The adoption of mining automation varied globally. Australia, Canada, China, Chile, and Brazil have the largest concentrations of commercial-scale AHS deployments in the world (Figs. 4 and 5; Table 2). Findings indicated that AHS deployed around the world were produced by the following companies: Pronto, Caterpillar, AST, Komatsu, Liebherr, Volvo, Scania, SafeAI, XEMC, Hitachi, Belaz, and Hexagon (Figs. 4 and 5). The AHS deployments pinpointed in Fig. 4 were performed by Codelco, BHP, and Vale. Imperial, Suncore, and Teck shown in Canada; Barrick (decommissioned), Newmont Goldcorp, and Freeport-McMoRan in the U.S.; and AngloAmerican in Peru; Teck, Codelco, and BHP in Chile; and Vale with several locations in Brazil. As for Fig. 5, AHS are deployed by Boliden in Sweden, Norsk Mineral in Norway, Ferrexpo in Ukraine, Suek in Russia, Spic in Mongolia, and BHP, Stanwell, Newmont Goldcorp, Maca, RioTinto, Fortescue, BHP and Roy Hill in Australia. As of 2023, Australia has the highest deployment of AHS (Table 2), with Western Australia having approximately 80% of the worldwide AHS deployments [72].

3 Methodology

Workshops were conducted to acquire qualitative and quantitative data. A workshop is a collaborative research method by which participants work as a group to identify problems and propose solutions through deliberations, information gathering and analysis. All relevant stakeholders and professionals in cutting-edge automation for mining applications were identified to unravel the barriers to automation in the mining industry. The Society of Mining, Metallurgy, and Exploration (SME), a global leader in information sharing and networking for engineering related professionals in the mining industry led the workshop effort and was uniquely positioned to identify and bring together participants in many industry sectors. SME Membership includes university researchers, global equipment manufacturers, suppliers, mine operators, consultants, government regulators, and other professionals in the mining industry who are intimately involved in technology and nearly every mineral commodity mined and processed in the US, and around the world. To select the participants, emphasis was given to soliciting input from a diversity of companies representing different segments of the mining industry, including focus groups (e.g., operators and contractors), mining methods (e.g., surface and underground), geographic location, and the types of mineral commodities being mined. Consideration was given to stakeholders who are recognized leaders in cutting-edge automation and have had experience implementing automation in mining operations. A total of 708 invitations were extended to knowledgeable professionals to participate in the workshops, representing 480 companies, of which 146 people participated (Table 3).

Workshops were organized in conjunction with existing conferences (Table 3). This cost-effective approach allows for sector-specific workshops, except for the SME MINEXCHANGE Annual Conference, which attracts a broad audience. Nine in-person workshops were held between 2022 and 2024 (Table 3). Eight of the workshops were organized during various conferences, as listed in Table 3, and a workshop was specifically organized for input from MSHA and the Mine Safety and Health Advisory Committee (MSHRAC) – a federal advisory committee to the NIOSH Office of Mine Safety and Health Research. Each workshop was led by at least three members of the research team, with 10 to 21 attendees (Table 3). Every workshop started with introductions and an overview of the challenges of mining automation. The broad discussion allowed the participants to focus specifically on issues identified by each group and ended with an hour-long breakout session. Breakout groups discussed the motivation for automation, company practice in research and capital projects, and barriers and drivers of automation in the U.S. mining industry.

Table 1 Summary of mining automation research (UK – United Kingdom, U.S. – United States)

Year	Country	Title	Problem addressed/ Automation area	Reference
1985	Australia	Robots and mining: the implications for Australian industry in the 1980's*	Discussed the conservative nature of the mining industry and presented ways to deploy robots for mining operations	[2]
2001	Australia	Recent advances in remote coal mining machine sensing, guidance, and teleoperation	Described a teleoperated robot vehicle with communications capabilities for underground coal mining	[21]
2005	South Africa	An Overview of the Automation of Load-Haul-Dump Vehicles in an Underground Mining Environment	A review of robots for the practical implementation of automated LHD trucks was presented, with sensor and model technology to improve navigation in underground mining discussed	[22]
2006	Australia	Autonomous excavation using a rope shovel	Early work on the autonomous mining rope shovel for coal mining was described with a concentration on digging, dipper fullness, dipper stall detection and monitoring.	[23]
2011	Canada	An interactive simulation model of human drivers to study autonomous haulage trucks	Developed a stochastic model to compare conventional trucks and AHS using various key performance indicators (KPIs)	[24]
	Australia	Assessing the impact of driverless haul trucks in Australian surface mining	Presented the social implications of the uptake of autonomous trucks in surface mining	[3]
	Canada	Autonomous haulage systems – justification and opportunity		[25]
	Australia	Autonomous and remote operation technologies in Australian mining	Presented a report of a day-long roundtable discussion on the social impact of mining automation.	[26]
2013	Australia	Why the mining industry needs a reference architecture for automation initiatives	Identified core challenges confronting reference architecture for mining automation and discussed the possible solutions to address the problems	[27]
2014	Germany	The data preparation for longwall workface automation with the shield-data based horizon control	Discussed difficulties with the data preparation from diverse sensors in underground coal mining and presented ideas to overcome data fusion problems for coal cutting automation	[28]
2016	Australia	3D robotic imaging of coal seam using ground penetrating radar technology	Developed an integrated system-level coal-strata sensing framework to improve coal mining automation	[29]
	U.S.	Autonomous vehicle technology: a guide for policymakers	Presented a guide for policymakers to improve autonomous vehicles for general transportation, not specific to mining	[30]
2017	South Africa	A survey on the degree of automation in the mineral processing industry	Presented an analysis of web-based questionnaire filled out by 55 mining/mineral/metallurgy professional respondents. The goal was to improve mineral processing automation	[17]
	Chile	Robotics research in Chile: Addressing the needs of the local mining industry at the Advanced Mining Technology Center	The Advanced Mining Technology Center of the Universidad de Chile discussed three developed autonomous technologies in partnership with the mining industry. The research was conducted between 2008 and 2012	[31]
	Netherlands	Autonomous machines emerging risks initiative – position paper	Discussed the expected challenges of autonomous machines (including mining) for the insurance industry. The focus was on potential failure and accidents that may occur using autonomous vehicles	[32]
2018	Canada/Chile	Plant automation for energy-efficient mineral processing	Discussed integration of multiple automation functions, including process control, to improve mineral processing and reduce energy demand for ore processing.	[33]
2019	Sweden	A step towards the design of collaborative autonomous machines: A study on construction and mining equipment	The thesis presented the state-of-the-art research with a focus on component connectivity and human-system integration for site management solutions	[34]
	Brazil	Approach of mining equipment performance with simulation of the use of autonomous trucks	Studied operational improvement by comparing the manual trucks to autonomous trucks using a simulation of data from Casa de Pedra Mine	[35]
	U.S.	Automation in U.S. longwall coal mining: A state-of-the-art review	Presented a comprehensive review of coal mining automation in the U.S. The authors discussed the reasons for no major improvements in the U.S. Longwall automation technology, but the regulatory barrier was not presented	[36]

Table 1 (continued)

Year	Country	Title	Problem addressed/ Automation area	Reference
	U.S.	Elements of Autonomous Shuttle Car Operation in Underground Coal Mines	Designed, constructed, and tested a laboratory-scale shuttle car model in a mock mine plan, with several simulated navigation scenarios in a room and pillar section of a coal mine.	[37]
	Australia	New technology & innovation: Report 2 – autonomous mining equipment	Reported review of autonomous mining equipment and suggested ways to drive mining automation	[38]
	US/Ghana	The future of mining in Ghana: Are stakeholders prepared for the adoption of autonomous mining systems?	Surveyed the mining stakeholders' perception on autonomous mining examined the university curricula for capacity building towards the adoption of mining automation	[39]
2020	U.S.	Adoption of autonomous mining system in Pakistan – Policy, skillset, awareness and preparedness of stakeholders		[40]
	Brazil	Analysis of mobile communication coverage and capacity for automation in open-pit mines	Presented the 7-year results of studies conducted to understand the crucial effect of network communication in automating open-pit mining operations	[41]
	Australia	Transformation of the Australian mining industry and future prospects	Discussed advanced information and communication, and AHS as part of the future of mining advancement in Australia	[42]
	Germany	Automation and digitization potentials of underground mining methods: A comparative analysis and identification of key performance indicators	The thesis examined the potential adoption of automation in underground mining methods with their KPIs	[43]
	Poland	Automation and robotization of underground mining in Poland	Presented the adoption and deployment of AI and automation in Poland mining industry	[44]
	Russia/ Kazakstan	Current state and development prospects of autonomous haulage at surface mines	Reviewed the problems causing the slow adoption of AHS in surface mining	[45]
	Australia	Human-systems integration for the Safe implementation of automation	Discussed human-related issues that need to be considered when implementing automation in the mining industry	[46]
	China	Bridging the physical, the digital, and the social	Presented the Internet of Things (IoT) technological advancements with autonomous mining	[47]
	Australia	Mine planning and selection of autonomous trucks	Discussed expected changes in mine planning due to autonomous trucks	[48]
	Japan	Safety concept and architecture for autonomous haulage system in mining	Presented the concept and architecture of AHS with system safety considerations	[49]
2021	Chile/ Australia	Automation and robotics in mining: Jobs, income and inequality implications	Discussed the socioeconomic impact of mining automation	[50]
	Egypt/Uk/ Saudi Arabia	Autonomous haulage systems in the mining industry: Cybersecurity, communication and safety issues and challenges	Reviewed the challenges of AHS with a focus on data management and data safety	[51]
	Canada	Environmental impact improvements due to introducing automation into underground copper mines	Proposed a life-cycle assessment model for underground mining automation with a focus on environmental impact improvement	[52]
	-	System safety for autonomous mining	The white paper presents a system safety approach for the deployment of automation system in the mining industry	[53]
	Morocco	Infrastructural requirements for the implementation of autonomous trucks in open-pit mines	Presented infrastructure and implementation criteria for automation in surface mining	[54]
	Austria	Recent developments towards autonomous tunneling and mining machinery	Reviewed autonomous machinery in tunneling and underground mining	[55]
	Australia	Robotic autonomous systems for earth-moving equipment operating in volatile conditions and teaming capacity: a survey	Surveyed robotic autonomous systems (RAS) for the improvement of automation in construction and mining industry	[56]
	Australia	Skills development and training of future workers in mining automation control rooms	Discussed the challenges of a shortage of skilled controllers for mining automation and proposed improved training to bridge knowledge gap	[57]
2022	India/ Saudi Arabia	Autonomous vehicles and intelligent automation: Applications, challenges, and opportunities	Reviewed artificial intelligence, machine learning, and IoT in autonomous vehicles by comparing their methodology and applications	[58]

Table 1 (continued)

Year	Country	Title	Problem addressed/ Automation area	Reference
	China	Review on improvements to the safety level of coal mines by applying intelligent coal mining	Presented the development in intelligent coal mining in China with emphasis on improved safety of workers	[59]
	Canada	Towards autonomous tailings and pit lake monitoring with amphibious robots	Review gaps and challenges for full autonomy of tailings monitoring and management	[60]
2023	Australia	Automation and artificial intelligence technology in surface mining: A brief introduction to open-pit operations in the Pilbara	Reviewed the AI and automation in surface mining with a presentation of resource development stages.	[61]
	Chile/ Colombia	Evaluation of the overall effectiveness (OEE) of autonomous transportation system (AHS) equipment and its impact on mine design. Open pit mine case study	Assessed the impact of implementing AHS on open-pit mine design	[62]
2024	UK/Japan	Decentralised motion planning for autonomous mining haulage trucks using prioritised multi-agent MPPI	Decentralized motion planning method for collision reduction was developed for AHS	[63]
	South Africa	Integrated and intelligent remote operation centres (I2ROCs): Assessing the human–machine requirements for 21st century mining operations	The authors reviewed the I2ROCs for human–machine integration and developed a framework for future collaborative I2ROCs development among the mining stakeholders	[64]
	Greece/ Sweden	Review of automated operations in drilling and mining	Presented a detailed review of automated operations toward future fully autonomous face exploration and drilling operations	[65]
	U.S.	Equipment and operations automation in mining: A review	Progress in the deployment of automation in mining operations was presented	[66]
2025	-	Human systems integration for mining automation	Focused on the technical and human-related factors in mining automation	[67]
	Australia	Industrial progress of robotic automation in mining applications: A survey	Reviewed robotic automation in the mining industry with a focus on industrial implementation	[68]
	China	Open-pit mine autonomous truck dispatching: Many-objective joint optimisation strategy considering uncertainties	Presented a model to reduce autonomous truck transportation costs by considering uncertainties in open-pit mining	[69]
	Canada	The social license to automate in the mining industry	Discussed the implications of deploying automated equipment on the social license to operate	[70]
	China	Autonomous driving of trackless transport vehicles: A case study in underground mines	Presented a cost-effective light-band-guided autonomous driving system for underground mining, offering improved safety and transportation efficiency through a digitally controlled light system	[71]

The participants at the first workshop (SME 2022 Arizona Conference) coalesced quickly around a set of barriers affecting the uptake of automation in the U.S. mining industry. The identified barriers include regulation, economics, social license, corporate willingness and technology readiness. Regulation refers to the U.S. MSHA regulations 30 C.F.R. Parts 1-199 [73]. The economic barrier refers to the cost of automation, particularly since automating one area of a mine will necessitate changes to other systems. It also includes the risk associated with lost production and change management. In this study, technology readiness refers to hesitancy to adopt technology that has not already been well proven at other sites, and a concern that technology is not mature enough to effectively operate in a mine environment without significant economic and functional risk. Corporate willingness means strategy and attitude, along with risk tolerance associated with investment. Social license referred to the communities, associated workforces, and environmental, social and governance (ESG) initiatives. Subsequent workshop participants agreed that these are the primary barriers. Based on group deliberation in each workshop, these barriers to the uptake of automation were ranked. It is interesting to note that though participants unanimously agreed on the identified barriers, the percentage ranking contribution to autonomous uptake differed significantly based on the commodities produced, mining method, and region of the mining company.

In addition to the nine workshops (Table 3), meetings were held with MSHA Leadership, and miscellaneous professionals from NIOSH, SME and academia (Table 4), with

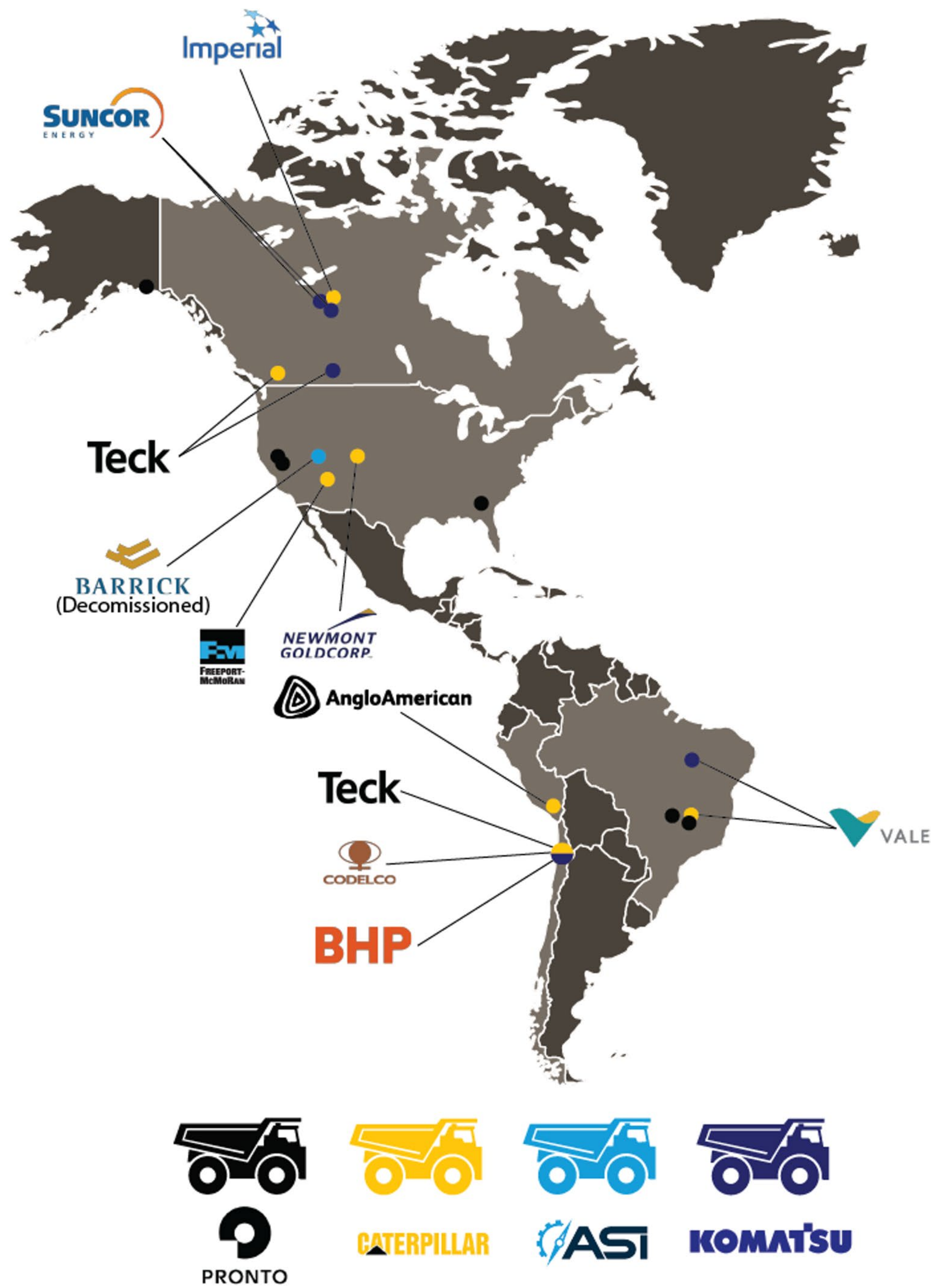

Fig. 4 North & South American AHS Deployments. This Fig. shows a grayscale map of North and South America pinpointing the deployment of AHS made by the following companies: Pronto, (7 black dots), Caterpillar, (7 yellow dots) AST, (1 blue dot) and Komatsu (5 purple dots) and deployed by the following companies: Imperial, Suncore, Teck, Barrick, Freeport-McMoRan, Newmont Goldcorp, and AngloAmerican

a total of 139 participants. These online virtual meetings were conducted with a focus on unravelling the regulatory barriers to mining automation in the U.S. These meetings diverged from a typical standard workshop model, where they were based on an open discussion with an emphasis on identifying regulation barrier to mining automation in the U.S. Findings show that MSHA regulations are broadly segregated by industry sector. Regulation 30 C.F.R. Parts 56 and 57 regulate surface and underground metal and nonmetal mines, respectively, while regulation 30 C.F.R. Parts 75 and 77 regulate surface and underground coal mines, respectively [73]. Those regulations were reviewed to determine their effects on automation in the mining industry. Our review of the regulations addressed four general types of potential barriers to automation. First, does the regulation require a person to conduct a certain activity that might otherwise be conducted through some other method? Second, does the regulation require that equipment be attended or operated by a person? Third, does the regulation require that features (such as seat belts, for example) be installed

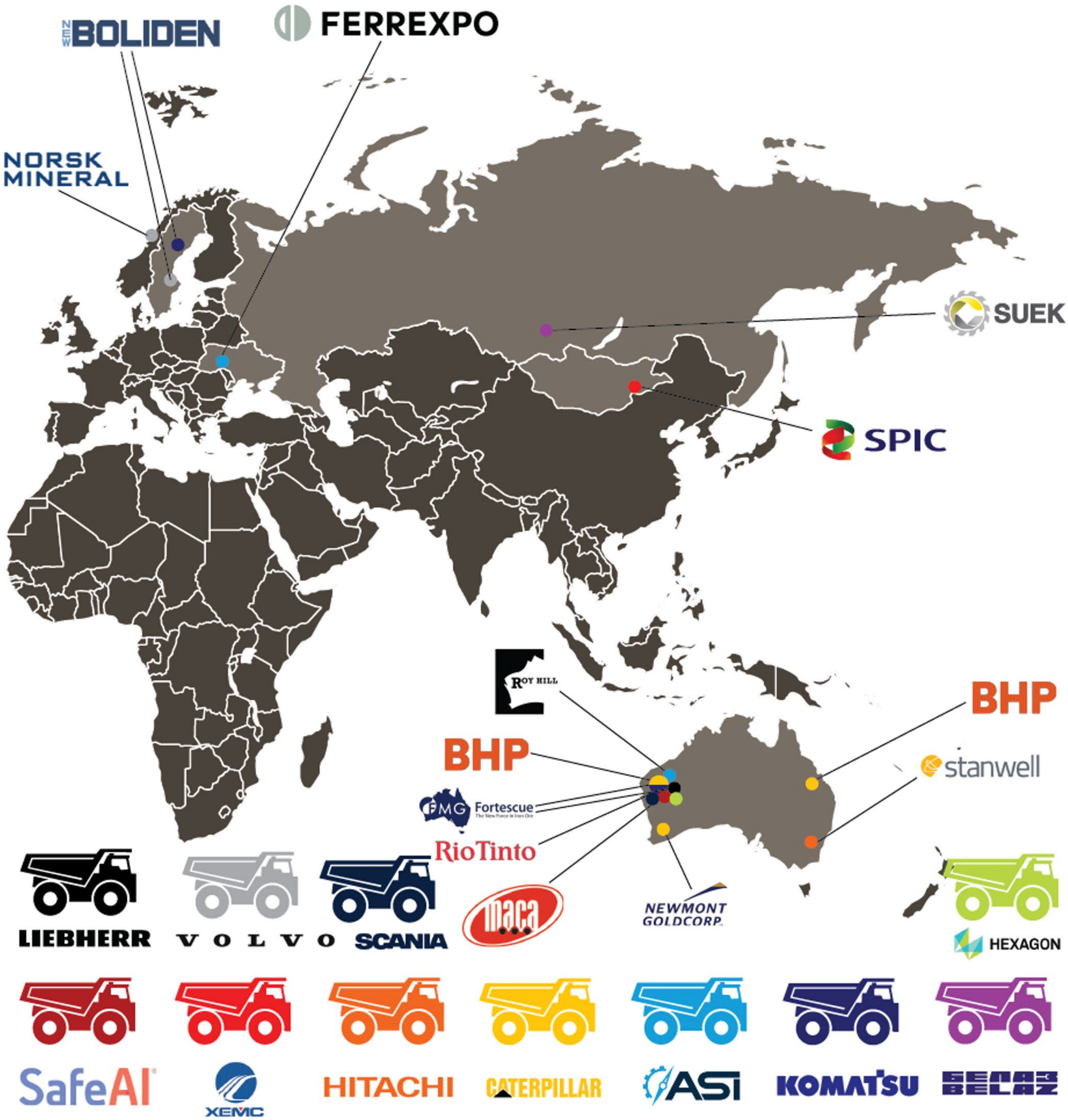

Fig. 5 European, African, and Australasia AHS Deployments. This Fig. shows a grayscale map of Europe, Africa and Australasia pinpointing the deployment of AHS made by the following companies: Liebherr (2 black dots) Volvo (2 Gy dots), Scania (1 navy blue dot), SafeAI (1 dark red dot), XEMC (1 light red dot), Hitachi (1 orange dot), Caterpillar (3 yellow dots), AST (2 light blue dots), Komatsu (dark purple, no dots shown), Belaz (1 light purple dot), and Hexagon (1 green dot) and deployed by the following companies: Ferrexpo, New Boliden, Norsk Mineral, Suek, Spic, BHP, Stanwell, Newmont Goldcorp, Maca, Rio Tinto, and Fortescue

in equipment that would not be necessary for safety if no human were operating it? Fourth, there is a miscellaneous category for regulations which could potentially create a barrier to automation, but which do not easily fit into another category.

In addition to regulations discussed above, there are regulations governing the certification of a wide range of equipment for use beyond the last open crosscut in underground coal mines, considered by definition to have the possibility of containing an air-methane mixture, and in certain

Table 2 Global deployment of AHS as of December 2023 (Data extracted from [72])

Country	AHS deployment (%)
Australia	57
Brazil	5
Canada	19
Chile	5
China	8
Norway	0.5
Peru	2
Russia	0.2
Spain	0.1
Sweden	0.9
Ukraine	1.2
U.S.	1.1

Table 3 Workshops (WS) held between 2022 and 2024 (PCMIA – Pittsburgh Coal Mining Institute of America; NSSGA – National Stone, Sand, and Gravel Association; MSHA A&CC – MSHA Approval and Certification Center)

WS	Month, Year	Location (USA)	Conference	Attendees
1	Dec. 2022	Tucson, AZ	SME Arizona Conference	21
2	Feb. 2023	Denver, CO	MINEXCHANGE 2023 SME Annual Conference	17
3	April 2023	Virginia, MN	SME Minnesota Conference	15
4	June 2023	Boston, MA	Rapid Excavation and Tunneling Conference	16
5	Aug. 2023	Phoenix, AZ	Hydrometallurgy 2023	24
6	Oct. 2023	Canonsburg, PA	SME PCMIA Conference	17
7	March 2024	Nashville, TX	NSSGA Conference	12
8	April 2024	Triadelphia, WV	MSHA A&CC and NIOSH Federal Advisory Committee	14
9	June 2024	Elko, NV	Elko Mining Expo	10

Table 4 Meetings held to discuss regulatory barriers to mine automation

Month, Year	Meeting/Event	Location	Attendees
March 2024	Meeting with MSHA Group	MSHA Offices, Arlington, VA	9
July 2024	SME Membership Mixer	Online virtual meeting hosted by SME	30
Sep. 2024	NIOSH Automation Partnership Meeting	Online virtual meeting hosted by the School of Mining Engineering and Mineral Resources, University of Arizona	50 (estimated)
Oct. 2024			50 (estimated)

gassy metal and nonmetal mines. Those regulations are set out in 30 C.F.R. Parts 6 (Testing and Evaluation by Independent Laboratories), 7 (Testing by Applicants and Third Parties), 15 (Explosives), 18 (Electrical Motor Driven Mine Equipment and Accessories), 22 (Portable Methane Detectors), 23 (Telephones and Signaling Devices), 27 (Methane Monitoring Systems) and 36 (Diesel Powered Mobile Equipment) [73]. Collectively, these are commonly referred to as the Permissibility Regulations and are not specifically addressed in this paper. They are, however, referenced since a number of characteristics stemming from these regulations could have a substantive impact on the adoption of innovative or automated equipment. Previous studies suggested that Permissibility Regulations contributed up to 63% barriers to commercialization and adoption of new technologies in the U.S. underground mining [74]. The following questions guided the discussion during the meetings (Table 4):

- What concerns does MSHA have regarding the development of automation relative to the current regulatory requirements and MSHA's mission?
- How do MSHA and NIOSH collaborate on emerging issues resulting from increasing automation in the mining industry?
- In general, how long does it take to achieve certification for permissibility of a new technology in coal and gassy status mines? What is the relative cost of the process?
- What are your concerns about the implementation of technology?

4 Results and Discussions

4.1 Barrier to Mining Automation

The participants at the first workshop held in Tucson, Arizona in December 2022 with the SME Arizona Conference, included major copper operators and original equipment manufacturers (OEMs). One key factor, especially for large open pit copper mines was that the brownfield nature of U.S. operations makes implementation of technology more difficult. Many mines are quite old, and complex, and were not designed for automation. Another impediment to technical innovation identified by the OEMs and suppliers was the lack of market size and potential to amortize research, equipment/system development, and manufacturing relative to commercial sales. Among the five key barriers to autonomous mining in the U.S., they identified economics as the primary barrier to automation (Fig. 6). The second workshop that was held in Colorado in conjunction with the MINEXCHANGE 2023 Annual Meeting and Exhibit and had the most diverse group of participants, representing

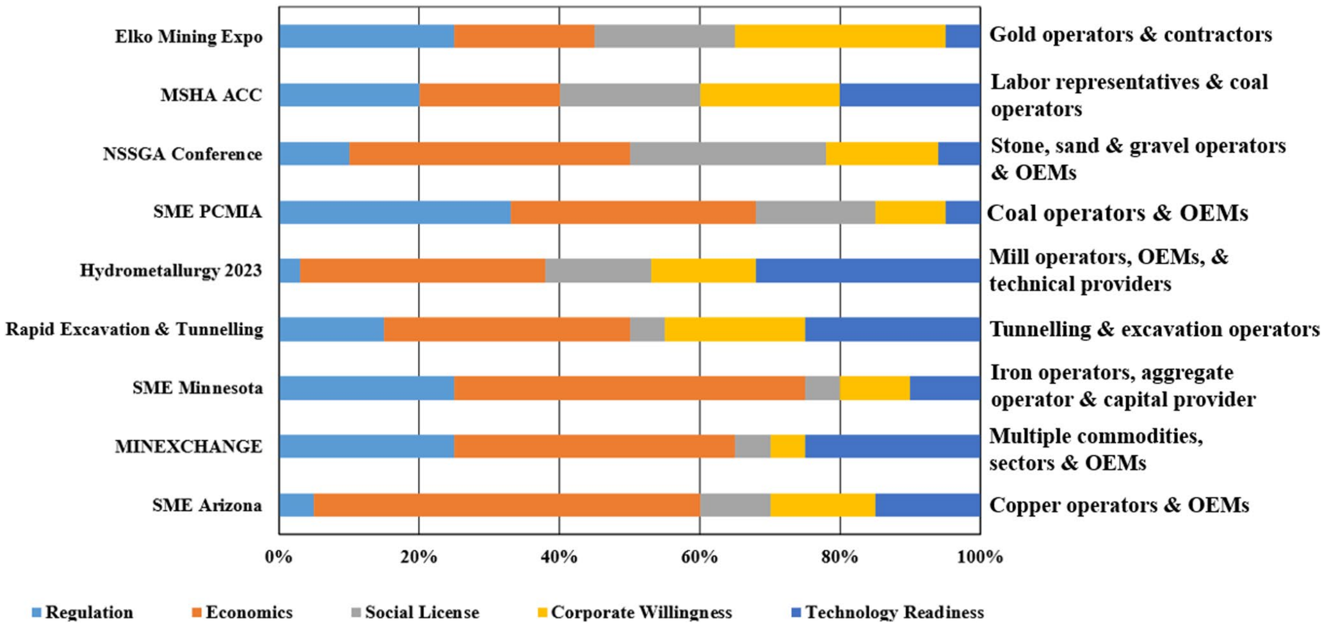

Fig. 6 Contributions of each of the five identified barriers to the uptake of automation in the U.S. mining industry, with primary sectors indicated, OEMs: Original Equipment Manufacturers

multiple commodities, sectors, and OEMs. There was a discussion of levels of automation, going from 1 to 10, with 10 indicating total autonomy. The participants deemed level 7 (system runs in an automated mode with monitoring and opportunity for operator intervention) as currently attainable, but 8–9 (fully autonomous) being quite difficult to achieve both legally and operationally. Finally, this group also identified economics as the primary barrier to automation, contributing 40% to the autonomous mining barrier. Regulation and technology readiness contribute 25% each and social license and corporate willingness contribute 5% each (Fig. 6).

The workshop participants at the SME Minnesota Conference consist mostly of iron range operators along with one aggregate operator and one mining venture capital provider. This group was less concerned about workforce issues as the region possesses a surplus of skilled workers. The operators in the region were primarily concerned about alienating the local community with automation and believe that collision avoidance is a high priority, so some phased adoption is likely. Like the first two groups, they also felt that economics was the largest barrier to uptake of automation and indicated that capital budgets are small for automation in this sector at this time. The workshop attendees at the SME Rapid Tunnelling and Excavation Conference (Boston, Massachusetts) felt that barriers to automation are iterative; and thus, it is difficult to identify one. After deliberation, like other groups, they identified economics as the primary barrier to automation. During the fifth workshop (Hydrometallurgy 2023), held in Phoenix, AZ, the participants were mostly processing plant and mill operators, OEMs, and other technical providers. There was recognition that maintenance is often hazardous and difficult in fully automated systems (e.g., repair and maintenance of large crushers). There was recognition that there are many OEMs and technical companies at work in a single plant or mill. Connectivity and data access are substantial issues. One operator who just suffered a major cybersecurity breach indicated that these challenges may worsen. Again, economics were identified as the primary barrier to automation.

The sixth workshop held in Canonsburg, Pennsylvania was primarily with coal operators and OEMs. Apart from the five key identified barriers discussed in Sect. 3, this group of attendees pointed out that Research and Development (R&D) departments are not as robust in the coal industry as they are in other mining sectors, and many companies simply do not have R&D departments or budgets – hindering technological innovation and implementation. However, the industry is safety-conscious, and companies always share safety ideas within the industry, including new technology. There was a sentiment that there is no appetite in the federal government to incentivize new technology in coal because there is generally not an appreciation for the need to mine coal in the U.S. However, President Trump's initiatives around coal may lead to investment in automation in the U.S. coal industry and the mining of metallurgical coal in the U.S. remains vital to steel production. Permissibility and MSHA approval are seen as a considerable barrier and economics as a slightly larger barrier (Fig. 6). The seventh workshop was held in Nashville, Tennessee in March

2023 with the National Stone Sand and Gravel Association (NSSGA) Conference. It consisted of stone, sand and gravel operators and OEMs. Given that most aggregate operations have traditionally been family-owned and operated and are locally significant in terms of employment and economic impact, social and community engagement are important considerations when making changes. Yet once more, economics were seen as the primary barrier to mining automation and social license is believed to also be a significant barrier to automation uptake in the stone, sand and gravel industry.

The eighth workshop was held in Triadelphia, West Virginia at the MSHA Approval and Certification Center following a NIOSH Mine Safety and Health Research Advisory Committee (MSHRAC) meeting in March 2024. Attendees included labor representatives, and coal operators, primarily from the MSHRAC members or their representatives, and MSHA personnel. Two barriers were identified for coal (versus metal and nonmetal): (I) the small market of domestic operators stifles innovation, and (II) the dynamic nature of the coal mine face also makes automation more difficult (as compared to a metal mine using mass mining methods like block caving and room & pillar). Technology ratcheting regulations were discussed and included communication and tracking, proximity detection, and potentially the new silica regulations. The group consensus was that it can be difficult to point to regulation as a barrier. However, prescriptive regulations can chill innovation. MSHA, like all sectors of the industry, is very concerned about the workforce – this concern may hinder support for mining automation. Additionally, it is difficult to maintain the A&CC and mine rescue equipment considering rapid technological innovation. This group found it somewhat difficult to coalesce around a percentage assignment to each barrier and assigned 20% each to Regulation, Economics, Social License, Corporate Willingness, and Technology Readiness (Fig. 6).

The last workshop (9) was held in Elko, Nevada in association with the Elko Mining Expo and consisted of major gold operators and contractors engaged in both underground and surface mining. A major theme was that the risk tolerance of the operator must increase with greater reliance on automation and autonomy. Further, systems must be properly designed for the specific mine environment. There was a feeling that OEMs are not always competent or interested in the specific factors influencing a particular operation. The availability of skilled labor was deemed important and needs to be considered. Labor cost savings should not be part of the assessment, but availability is critical, particularly in some remote areas. Many companies are near-sighted with respect to labor costs and do not understand the importance of upgrading labor skill sets with automation despite the increase in costs. This is seen as potentially disastrous for an operation. There was also considerable discussion of barriers posed by the limitations on communication frequency access and usage by Federal Communications Commission (FCC) regulations. There was a consensus that competitors in the mining industry would collaborate on technology to reduce risk or to address regulatory issues (e.g., the use of autonomous haul trucks and diesel particulate matter – DPM). This group saw regulation and corporate willingness as the major barriers to the integration of automation into their operations. The participants' weighted average of the nine workshops is presented in Fig. 7. As can be seen in this figure, economics, technology readiness, and regulation are the three most significant barriers to the acceptance of automation in the U.S. mining industry. These results agree with previous end-user requirement surveys conducted for autonomous vehicles in agriculture, lawn and turf care, material handling and construction (including mining) [75]. The

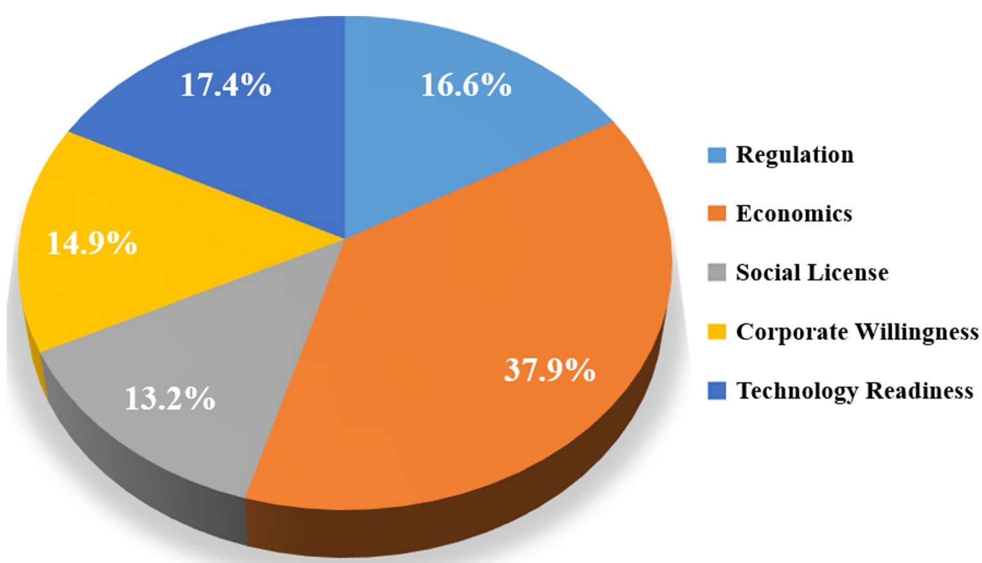

Fig. 7 Participants' weighted average of barriers to uptake of automation in the U.S. mining industry

survey results indicated that achieving lower total cost of operation (TCO), higher efficiency, and higher safety were the top factors that may drive the adoption of autonomous vehicles [75]. These factors are all related to economics, which is the most significant barrier to mining automation identified in this study. While economics and technology readiness mostly rely on the private sector (though the government may be able to stimulate investment in automation), regulation depends on the government. Even if economics and technology readiness barriers do not exist, government approval is required for the deployment of new technology that has not been previously allowed/approved. Approval of new innovative technology that was not perfectly envisioned when the regulation was promulgated may require regulatory review. Therefore, the MSHA regulation was reviewed to identify likely regulatory barriers to mining automation in the U.S., and the obtained results are discussed in Sect. 4.2.

4.2 Regulation Toward Improving Mining Automation in the U.S

The history of comprehensive mine safety and health regulations begins in the U.S. with the Mine Safety Act of 1891. While more modern requirements have largely replaced the substantive provisions of the statute itself, the statute is important because, rather than leaving detailed requirements to an administrative agency, the detailed mine safety requirements were included in the statute itself. As with the

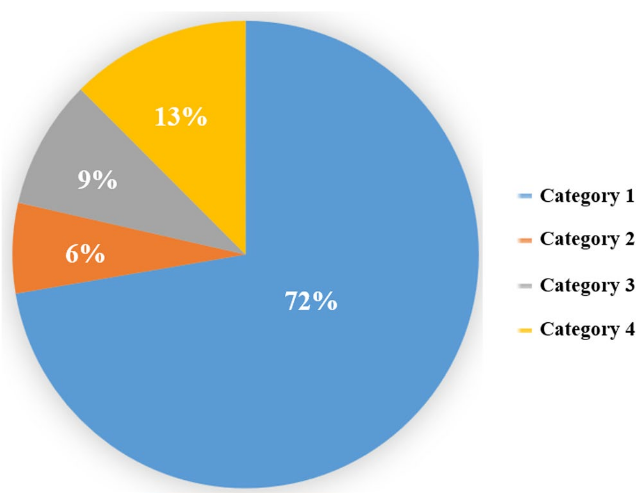

Fig. 8 Categories of regulation barriers to mining automation in the U.S. (as of April 14, 2025) (Category 1: The regulation requires that a "person" conduct or be present for a particular regulatory function, Category 2: The regulation requires that equipment be "attended", Category 3: The regulation requires that ancillary features such as seat belts or rollover protection be installed in equipment with no exception for fully automated equipment, Category 4: Regulations which could be considered to impede automation but are not easily placed in one of the categories above)

1891 Act, much of the code has been replaced over time, but several fundamental aspects of the code, such as the requirement for preshift examinations, have remained essentially unchanged. The statute under which MSHA now operates is an amendment of the 1969 Coal Mine Health and Safety Act. Title III of that statute contained interim mandatory safety standards for coal mines. The statute was amended in 1977 to, among other things, create MSHA, include jurisdiction over non-coal mines and move the agency from the Department of the Interior to the Department of Labor. However, the amendment left the old interim mandatory standards from 1969 in place. In the U.S., mine safety regulations have historically been embedded in statute. Since some current regulations remain there, it impedes MSHA's ability to amend them as conditions and technology change. Changing regulatory requirements would require amending the statute rather than simply promulgating new rules.

As discussed in Sect. 3, regulatory barriers to mining automation in the U.S. were classified into four categories:

- Category 1: Required a person to perform some regulatory functions, limiting the use of automated equipment.
- Category 2: MSHA specified that equipment should be attended, suggesting that full automation was not considered.
- Category 3: The regulations that require ancillary features to be installed in equipment without exception for fully automated equipment.
- Category 4: Other observed regulations with the potential to cause a barrier to mining automation but do not fall into Categories 1 to 3.

Findings indicate that there are approximately 98 regulations (including sub-regulations) dealing directly with extraction activities, which were identified as presenting some potential barriers to automation or innovation in the U.S. mining industry. Of these, 76% of the identified regulations explicitly require a "person" to conduct a required activity or function or at least be present for it (Fig. 8). Conversely, 6% of the regulations explicitly require that equipment be "attended" to when in use and 9% regulations explicitly require installation of features, such as seat belts or rollover protection, in equipment that is only necessary if a person is operating the equipment, while 13% regulations present potential barriers to automation or innovation that are not easily characterized by the other three categories (Fig. 8). Even if these observed regulations are modified to allow full automation, the mining industry may still face approval challenges because only one relatively small MSHA unit was devoted to the approval and testing of equipment. It was hoped that promulgation of rules allowing for third-party testing a certification in 2003 (30 C.F.R. Part

6) would help to provide additional resources and generally speed up the approval process. However, those regulations allowed for the use of third-party testing and approval only if their criteria provided at least the same level of protection afforded by the MSHA approval requirements. The same MSHA office that does the review and certification of equipment also conducts that review. As of April 2025, MSHA has approved only the International Electro-technical Commission ("IEC") to conduct such evaluations [76], but has required that certain of its criteria be modified to meet MSHA regulations.

Further review shows that 30 C.F.R. Part 7, which contains detailed testing requirements for several different systems (including brattice cloth, ventilation tubing, battery assemblies, multiple shot blasting units, electric motor assemblies, electric cables, signaling cables, cable splice units and refuge alternatives) was first promulgated in 1988. In the same year, 30 C.F.R. Part 15, which covers the approval of explosives and sheathed explosive units, was promulgated. Also, 30 C.F.R. Part 18, which largely covers permissibility requirements for all electrically driven equipment and accessories, was promulgated over 50 years ago in 1968. Various parts of these regulations have been amended over the years; 30 C.F.R. Part 7 and Part 18 were amended in 2008 and 1992, respectively. It is safe to conclude that during the period between the promulgation of these regulations and today, much technology has changed. 30 C.F.R. Part 18 regulations were developed before the invention or adoption of most of the digital technology in use today. Given their age, these regulations present a significant barrier to the adoption of any newer technologies in areas where permissible equipment is required. As a result of the obsolescence of these standards, permissible versions of many currently used pieces of equipment, such as survey instruments, Powered Air Purifying Respirators (PAPRs) and hand-held radios are not available. As a result, their use is only made possible through the Petition for Modification process (See 30 C.F.R. Part 46), which must be considered on an individual mine-by-mine basis. This results in significant inconsistencies between enforcement districts and generally hampers the adoption of these more advanced technologies.

Moreover, 30 C.F.R. Part 22, which governs approval of portable methane detectors essentially states that a portable methane monitor will be approved if it meets the requirements of Bureau of Mines Schedule 8c, which went into effect October 31, 1935, and was amended by a supplement issued in April 1955. While detector technology may or may not have changed significantly in the last 69 years, it is likely that the way in which the detected levels are communicated to and interact with mine equipment and personnel have changed significantly during that period. 30 C.F.R. Part 23, which covers approval of telephones and signaling devices largely finds its source in 1955, and, although it has been amended over time, the last substantive amendment to that section appears to have been in 1982, which was almost 10 years prior to the introduction of the first digital cell phone. The substantive criteria for approval of methane monitoring systems in 30 C.F.R. Part 27, appear to have originated in 1966 and do not appear to have been amended since then. Similarly, the substantive requirements for design and construction of permissible diesel-powered diesel transportation equipment in 30 C.F.R. Part 36 originated in 1961 and appear to have been last amended in 1996.

In addition to the age of the regulations, there are two additional factors which impede the approval of new or innovative equipment. First, MSHA does not devote a great deal of its resources to the approval and certification of new equipment. Because of that, approvals of new equipment are now well over a year on average. Since the approval process cannot take place until detailed design and material specifications have been developed, manufacturers are reticent to invest in design and specification because assurance that the equipment will eventually go to market remains uncertain. Second, the amount of information required by MSHA for review makes it essentially impossible for the consumer of the equipment to seek approval. This means that the manufacturer must be the party interacting with MSHA to gain approval. The market for permissible mining equipment is quite small, and thus it is generally not economical for a manufacturer of equipment primarily intended for a different market to spend the time, financial resources, and effort gaining approval for a product that is ultimately to be sold only to a handful of potential customers. This is especially true for equipment which has already been tested and deemed intrinsically safe by an independent third-party laboratory or other government authority. This issue inhibits the transfer of technology between industries at the expense of the mining sector. Another regulatory factor that may be of potential barrier to mining automation in the U.S. is the Federal Communications Commission (FCC) radio frequency issues [77]. The interdependence of technology within mining requires the use of wireless technologies in providing functionality and safety, and it is crucial as the Internet of Things (IoTs) is being widely adopted in the mining industry.

To resolve the regulatory impediment to mining automation in the U.S., the authors reviewed the international regulations on mining automation with a focus on countries with successful records in automation. Findings indicated that, unlike the U.S., mine safety in countries with higher deployment of AHS (Table 2), including Australia and Canada, is governed by state or provincial level regulations, rather than Federal. For instance, in Western Australia (the region with the highest AHS deployment in the world), the Department of Mines, Industry Relations, and Safety (DMIRS) only provides a guideline for compliance rather than enforceable regulations [78]. This is due to the structure of their regulatory framework which places a much larger burden on the mine managers. "Safe mobile autonomous mining in Western Australia" (the Code) is designed to provide guidance on: mobile autonomous and semi-autonomous systems used in surface and underground mines; developing and evaluation safe work procedures for those systems; the control of autonomous loaders, trucks and other mobile equipment, such as drills and dozers; and identifying the unique risk profiles in relation to mobile autonomous mining systems. Western Australia's maturity of mining regulations has influenced the other states to adopt Western Australia's regulations and certifications as their own or to slightly modify those regulations to fit their specific jurisdiction. These regional regulations allow specific challenges to be addressed and encourage the uptake of mining automation. Australia is considered to have a "duty of care" standard in place. Implementation of a "duty of care" standard under the U.S. Mine Act would be problematic, since the statute prescribes "strict liability" for any violation. Australian guidelines have been utilized as a basis for many of the other countries' approaches to regulation.

Like Australia, Canada also appears to have effective regulations in place for automated equipment. In January 2020, Alberta OHS issued their approval process for AHS [79] based on OHS Act Sect. 56. This standard was developed through cooperation with Western Australian AHS sites and specifically calls out ISO 17,757: Earth-moving machinery and mining - Autonomous and semi-autonomous machine system safety [80]. The approval process is site-specific and may vary based on specifics of the mine site, technology, systems, and the site operator's experience with the AHS system. It should be noted that this regulation was not developed until after many of the oil sands mines had already implemented AHS. Specifically, Alberta Canada's Occupational Health and Safety (OHS) regulations are the first enforceable regulations for AHS and reference international standards [79]. Worldwide pressure from industry groups like Global Mining Group (GMG) has begun pressing for the adoption of international standards such as Functional Safety to analyze AHSs [81]. With the roll-out of the Alberta OHS regulations, international standards are becoming an enforceable document. Those standards (Table 5) already govern many of the aspects of the base haul trucks. The addition of functional safety into the enforceable standards is enabling a quantitative or semi-quantitative process to evaluate a very complex system's safety. Standards (Table 5) are generally not mandatory in comparison to regulations unless that standard is referenced

Table 5 List of some standards that would apply to an AHS

Standard	Title	Type
ISO 31,000	Risk Management Package	A
IEC 60,204	Safety of Machinery – Electrical Equipment of Machines	B1
IEC 61,025	Fault Tree Analysis	A
IEC 61,310	Safety of Machinery – Indication, Marking and Actuation	B1
IEC 61,508	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems	A
IEC 61,511	Functional Safety – Safety Instrumented Systems for the Process Industry Sector	B
IEC 62,061	Safety of Machinery – Functional Safety of Safety-Related Electrical, Electronic and Programmable Electronic Systems	C
ISO 9001	Quality Management Systems – Requirements	A
ISO 12,100	Safety of Machinery – General Principles for Design – Risk Assessment and Risk Reduction	A
ISO 13,849	Safety of Machinery – Safety-Related Parts of Control Systems	B1
ISO 14,121	Safety of Machinery – Principles for Risk Assessment	A
ISO 15,998	Earth-Moving Machinery – Machine-Control Systems (MCS) Using Electronic Components – Performance Criteria and Tests for Functional Safety	B1
ISO 16,001	Earth-Moving Machinery – Object Detection Systems and Visibility Aids – Performance Requirements and Tests	C
ISO 17,757	Earth-Moving Machinery and Mining – Autonomous and Semi-Autonomous Machine System Safety	C
ISO 19,014	Earth-Moving Machinery – Functional Safety	C
ISO 19,296	Mining – Mobile Machines Working Underground – Machine Safety	B1
ISO 20474-1	Earth-Moving Machinery – Safety – Part 1: General Requirements	B1
ISO 21,815	Earth-Moving Machinery – Collision Warning and Avoidance	C
ISO 26,262	Road Vehicles – Functional Safety	A

in a regulation, such as ISO 17,757 in the Alberta OHS Regulation [80]. Additional standards required for manned operations will also be required for AHS sites (Table 5). An example of a required standard for manned sites that would also be required for an AHS is European Standard (EN) ISO 12,100 Standard "Safety of Machinery – General Principles for Design – Risk Assessment and Risk Reduction" which describes the requirements for safe design principles [82]. The use of comparable international standards that have similar or higher protection to miners as that of MSHA regulations has been suggested in the literature to improve uptake of new technology in U.S. coal mining [15].

Unlike the DMIRS Guide, the OHS process is a set of specific regulations rather than a guide. Within these regulations are prescriptive requirements for international standards that must be met. A required portion of the application is a compliance letter either from the manufacturer of the equipment being used or an Alberta Professional Engineer indicating that the applicable requirements of ISO 17,757 are met [80]. This flexibility is lacking in the MSHA regulations due to the statute of the Mine Safety and Health Act of 1977. The MSHA regulatory challenges need to be resolved to pave the way for fully autonomous mining in the U.S. MSHA is aware and acknowledges that technology is currently evolving at a rapid pace, and they recognize the need to increase their capability in approving and certifying technology. Furthermore, MSHA understand that they "must keep pace with technology to achieve their mission and remain relevant." Unfortunately, MSHA is significantly hampered in facilitating the needed changes due to shortfalls in labor and budget constraints. At present, the vast majority of their budget is allocated for enforcement as a requirement of the law. They are attempting to be responsive to these changes in technology by reinterpreting existing regulations and promoting technology that supports the MSHA mission and addresses immediate health and safety priorities affecting miners. As a government entity, they are obligated to follow their congressional mandate. It was noted on several occasions during our discussion (Table 4) that MSHA wants to change the perception in the industry that MSHA represents a barrier to the development and use of new technology in the mining industry. They want to promote and encourage technological improvements to make the mining industry safer and use the A&CC (Approval and Certification Center) to advance this cause. Furthermore, they emphasized the need to make the approval and certification process associated with permissibility more transparent and collaborative. Such initiatives for improved certification and permissibility of the use of "electric motor-driven mine equipment and accessories" in gassy mines were recently implemented by MSHA [83].

To change the perception in the U.S. mining industry that MSHA regulations hinder the adoption of new innovative technology, there is a need to offer possible ways to remove the regulatory barriers. Several paths could be taken to allow for more facile alignment of the regulatory environment with changing technology. First, of course, the statute could be amended to remove the "interim" standards in Title III and adjust the existing language to allow for more regulatory flexibility. That would, of course, literally take an act of the U.S. Congress. Although not likely, the obvious advantages of evolving technology could create a push to make it happen. Second, MSHA could undertake to promulgate new regulations that would replace those most problematic to the adoption of automated systems (Categories 1–4). There are two potential approaches to this issue. One approach would be for MSHA to propose modifying the definition of "attended" and add a definition of "person" to embody the safety purpose of the regulations currently using those terms, but without the physical presence of a person in certain, defined circumstances. At the same time, and in the same rulemaking, the MSHA could also provide an exception for automated equipment to those regulations requiring personal protective equipment such as seat belts. As discussed above, MSHA could also develop a set of written criteria or guidelines that would formalize interpretations of the existing standards to account for automation. Of course, MSHA could engage in a regulation-by-regulation review for each of its regulations that might impede automation or innovation. The disadvantage to all of these approaches is that the promulgation process requires a large amount of agency resources and faced with a finite budget and rigid mandatory inspection requirements could put an unacceptable strain on agency operations. The other disadvantage to this approach is that virtually every major rulemaking that MSHA has engaged in over the last 20 years has faced legal challenges. These challenges not only further strain agency resources but also require additional personnel for legal support. Finally, Sect. 101(c) of the statute allows interested parties (that is mine operators or miners' representatives) to petition MSHA to modify an existing regulation on one of two grounds: (1) An alternative method of achieving the result of the standard exists that will, at all times, guarantee no less than the same measure of protection afforded by the existing standard, or (2) Application of the existing standard will result in a diminution of safety to the miners. Use of this provision would allow miners and mine operators to demonstrate to MSHA that certain automated systems would be as or more safe than existing systems and/or that use of existing systems when others are available would represent a diminution of safety to the miners. While it may be the case that equipment manufacturers might be better positioned to present the kind of information necessary to meet these standards in regard to automation, the current regulations require that an application for modification may only be made by the mine operator of the affected mine or a representative of miners at such mine. In addition, each application can only be made regarding a single, specified mine. Thus, the regulations would have to be amended in order to allow anyone other than a mine operator or representative of miners to apply and for the resulting modification to apply to more than one single mine.

4.3 Drivers of Mining Automation

The workshop participants held at the SME 2022 Arizona Conference identified a need for a collaborative relationship between the mining industry and regulators, and they cited the EMESR (Earth Moving Equipment Safety Roundtable) in Australia as a good example [84]. They also felt strongly that small operators need the most assistance around automation from both NIOSH and MSHA. They saw key drivers in the U.S. for the uptake of automation as a lack of workforce and demand for low-carbon technology. The participants acknowledged that automation will not reduce the workforce considerably in the short to medium term, but it will allow for more diversity in hiring and flexibility for workers. They argued that a workforce for automation will require upskilling – this may open opportunities for workforce development in universities and change or improvement in curricula to allow the needed skills. This submission agrees well with that of the participants of the second workshop (MINEXCHANGE 2023 SME Annual Conference, Denver, CO). Contrary, the attendees at the third workshop (SME Minnesota) were less concerned about the workforce, as the region boasts skilled workers, suggesting that the skilled workforce may boost the uptake of mining automation in the region. It is important to note that when autonomous LHD was employed at El Teniente Copper Mine (Chile), the system replaced sixteen operators and two mine supervisors – suggesting a change in workforce trajectory if autonomous mining is widely adopted [3]. Previous stakeholder engagement in Australia suggested that a fully autonomous system may lead to 30–40% reduction in the workforce, equivalent to about a 50% reduction in operational roles [26]. The main issue that may arise is that aboriginal personnel will likely be affected, as research shows that 50% of the workforce are semi-skilled workers (mostly from the host community) and 20% are trainees on internships [26]. In coal mining, approximately 40% labor work may be replaced by automated equipment, which improves mine safety, however, this presents significant labor loss [50]. This may affect the corporate social responsibility approach of the mining company, and the host community may demand better community impact for social license to operate. However, more autonomous equipment maintenance workers will be needed, suggesting that the mining workforce may not be affected, but personnel will be needed in maintenance rather than in ore excavation operations. These changes in manpower needs for autonomous mining may lead to reduction in tax remittance to the government, which may affect economic activities [50]. A potential way to address the workforce challenges is to plan for personnel development programs, to upskill for mining automation, so that the loss of jobs will be minimal. Besides, skilled workers will also be needed for handling and protecting the data of computerized equipment to handle machine failures and complicated situations, including breakdowns in remote communication or router connections. There is currently a shortage of mine automation controllers, which calls for improved curricula for the capacity building of future mine automation workers [57]. Moreover, there are reports of the high rate of retirement of workers in the mining industry, coupled with a low rate of enrollment in mining programs, which may drive the adoption of autonomous mining. Early research shows that the fear of workforce reduction by artificial intelligence (AI) technology and autonomous systems (AS) may not be necessary as studies from 17 countries on the impact of AI/AS on workforce in agriculture, manufacturing, and utilities indicated that AI/AS did not reduce the human work hours but increased or changed the level of skill required for workers [85].

A key regulatory driver for autonomous uptake identified during the second workshop is exposure-based regulation (e.g., dust rules), particularly the new silica rule in the metal/nonmetal industry. This agrees with the submission of attendees of workshop four (rapid excavation & tunnelling workshop), which indicated that dust and environmental exposure are key drivers for mining automation. Attendees in this workshop (mostly tunnelling and construction professionals) indicated that labor shortages after the COVID-19 pandemic have driven the desire to adopt more automation in the U.S. Also, labor shortage in mostly remote mines has been reported to drive mining automation [26]. Further, a reduction in liability payments for injury or compensation for the death of workers due to mine collapse may drive mining automation.

A driver of mining automation identified during the Hydrometallurgy 2023 workshop (Phoenix, AZ) is the fixed plant nature of the mineral processing plants, which allowed for early and long-term adoption of automation. However, there is still a need to mimic the highly experienced and skilled metallurgists with sensing and data science. There was a general sense that standardization would be helpful. The coal mining professionals and OEMs (sixth workshop at the SME PCMIA Conference, Canonsburg, Pennsylvania, USA) believe that there is consistency in new technology across a single company's mines. They indicated that today's workforce is now more mobile (between shifts and operations), allowing technological and safety innovation to move more rapidly. Also, workforce shortages are felt to be a serious concern in coal mining, which may be a driver for mining automation. Nevertheless, labor representatives and coal operators (attendees of the eighth workshop) are supportive of technology that improves safety, including automation, and acknowledge that the nature of the workforce will change, but a reduction in workforce is unlikely in the short to medium term. However, there is a need to create a research and development department in each company to increase technology innovation and uptake across the industry.

The stone, sand and gravel industry (workshop 7; NSSGA Conference, Nashville, TX) felt that data ownership and security are key to the uptake of autonomous systems – the consensus being, "the machine owner owns the data." However, there is a need to improve cybersecurity for data safety [51]. Again, participants at the NSSGA workshop believe that the scarcity of skilled labor is driving automation. Careful integration of technology with the workforce is vital. It was emphasized that cost competitiveness is a major factor motivating technology. Improved safety, efficiency and economics may drive the uptake of mining automation. Bellamy and Pravica (2011) discussed that the adoption of autonomous LHD at El Teniente Copper Mine (Chile) improved productivity by 25% [3]. A report of over 550 operational autonomous haulage trucks produced by Caterpillar indicated up to 30% improvement in mining productivity, and no single injury was recorded in 900 million drives, as of May 2022 [86]. A case study of the economic evaluation of operational costs of fully automated trucks at "BHP Billiton Mt. Keith nickel mine" Australia, indicated that $32.7 million can be saved annually on labor costs [3]. Also, automation trucks increased machine utilization, increased machines' tyre and brake life (up to 40% compared to a conventional truck, according to Komatsu [86]), and improved fuel efficiency and mine safety [3]. These gains may drive an uptake of automation in mine operations. The earlier uptake of automation was higher in underground mining than in surface mining [3], but in recent years deployment of AHS is revolutionizing the surface mining operations. Earlier, autonomous equipment was designed for underground mining. Among the challenges is that autonomous machines designed for underground mining may not be suitable for surface mining operations due to variations in operational factors, including changing weather and road conditions in surface mining, wall sensing in underground mining, and sharing roads with the mining community in surface mining, limiting adoption due to strict regulations [3]. In the 2000s, the mining industry's embracing of new technology was slow due to concerns about interruption in production plans and a lack of commitment to financial support for new technology. In recent years, mining companies like Rio Tinto have invested in the research and development of new innovative technologies, which is driving the uptake of new technologies, including automation [3].

Another factor that may drive mining automation is the increasing demand for minerals due to the green energy initiative. According to the International Energy Agency (IEA) and other reports [86], demand for lithium will increase by 42 times the current demand by 2050, while other critical minerals may be six times higher than the current demand. To meet the demand for minerals in the future, the mining industry may need to adopt a high productivity system like autonomous trucks. The increased concerns for improved mine safety are another driver for adopting autonomous systems in the mining industry, as workers can work remotely away from dangerous mining zones. This concern is driving digital mining and robotic applications in underground mines [87, 88]. Moreover, automation will reduce long-term injury sustained in mining activities, coupled with a potential reduction in inhalation of dust exhaust fumes from conventional mining trucks [22]. Due to the repetitiveness of autonomous systems, variability in ore excavation, handling, and processing may be catered for, leading to better resource efficiency [86]. In addition, a potential decrease in global warming may drive mining automation, especially in countries with a target to reduce carbon emissions [52]. All these drivers may increase the global market of autonomous trucks from the current $1.6 billion to $12.5 billion by 2035 [89].

5 Conclusions

Adoption of mining automation is growing around the world, with widespread uptake in Australia and Canada. The barriers affecting widespread acceptance of mining automation in the U.S. were investigated by acquiring primary data using a workshop research model. 146 professionals related to mining automation participated in the workshops organized between 2022 and 2024. Five major barriers to mining automation in the U.S. are economics, technology readiness, regulation, corporate willingness, and social license. The workshop participants ranked these barriers, and results indicate that economics, technology readiness and regulation are the three most significant barriers to mining automation, contributing 37.9%, 17.4%, and 16.6%, respectively. These results indicate that the central assumption that regulation is the main barrier to mining automation in the U.S. is untrue.

From the perspective of equipment manufacturers and suppliers, the market for new technology in the mining industry is relatively small, where there is insufficient capacity to amortize research and development costs over a sufficiently large quantity of equipment sold to make innovation attractive. As such, different equipment manufacturers and suppliers during several workshops reiterated their concerns regarding the high cost of technology and automation and the limited opportunities for sufficient economic return as a major barrier to the implementation of technology in mining unless the technology could be readily adapted for use in construction or other industries. These economic concerns extended from financial risks associated with the failure of the technology to more conventional evaluation approaches related to cost-benefit type assessments, incorporating capital and operating costs and the expected benefits derived from the use of the technology. A common concern focused on unintended ramifications of technology utilization on other systems and the constraints associated with the lack of compatibility of implementing certain types of technology into mature operating environments. Besides technological risk, significant deterrents also included the perceived risks associated with the loss of production and the implications associated with change management. While still a consideration, it was the opinion of many that the influence of economics as part of the decision-making process associated with technology investment was lessened in situations involving safety and/or in order to achieve compliance with new tech-ratching regulations.

Participants believe technology readiness is a significant barrier to mining automation in the U.S., however, literature shows that countries like Australia and Canada have widespread adoption of mining automation. The review of regulatory frameworks of these countries indicates that both countries have effective regulations in place for automated equipment, which are region, site, and operator specific. The review of the U.S. regulations reveals that there are approximately 98 regulations with potential barriers to automation or innovation in the U.S. mining industry, mostly related to coal mining. Issues related to "Duty of Care," permissibility requirements related to the integration of technology in coal and gassy status mines, constraints associated with the FCC regulations, and the prescriptive regulatory structure in the U.S., were all perceived to be contributing factors responsible for impeding automation in some capacity depending on the industry sector. Furthermore, the regional differences in MSHA enforcement and the interpretation of regulations were also viewed as a concern and potential deterrent. In all, with the exception of coal, regulation was not perceived to be a primary barrier to automation as compared to economics and technology readiness. Two key paths could be taken to allow for more facile alignment of the regulatory environment with changing technology. First, the statute could be amended to remove the interim standards in Title III and adjust the existing language in the identified 98 regulations to allow for more regulatory flexibility, but it would require an act of Congress. Second, MSHA could undertake to promulgate new regulations that would replace those most problematic to the adoption of automated systems. A key regulatory driver for autonomous uptake is exposure-based regulation (e.g., dust rules), particularly the new silica rule in the metal/nonmetal industry. Also, the lack of workforce and demand for low-carbon technology is identified as a potential driver of mining automation. While MSHA is concerned about the potential impact of automation on the U.S. mining workforce, the participants acknowledged that automation will not reduce the workforce considerably in the short to medium term, but rather necessitate upskilling and diversification of the workforce. To drive the adoption of automation in the U.S. mining industry, Federal support toward the use of automation will improve investment in automation technology, which may solve the identified primary barriers.

Funding This work was supported by a grant from Centers for Disease Control and Prevention (CDC) (75D301-22-C-14149).

Data Availability The data obtained during the current study are available by contacting SME.

Declarations

Disclaimer The findings and conclusions in this article are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health or the Centers for Disease Control and Prevention.

Conflict of interest The authors declare no competing interests.

References

1. Schwab K (2016) The Fourth Industrial Revolution. World Economic Forum. CH-1223 Cologny/Geneva, Switzerland
2. Kassler M (1985) Robots and mining: The implications for Australian industry in the 1980's. Robotica 3:13–19. https://doi.org/10.1017/S0263574700001429
3. Bellamy D, Pravica L (2011) Assessing the impact of driverless haul trucks in Australian surface mining. Resour Policy 36:149–158. https://doi.org/10.1016/j.resourpol.2010.09.002
4. Onifade M, Said KO, Shivute AP (2023) Safe mining operations through technological advancement. Process Saf Environ Prot 175:251–258
5. Miyashita K, Kawaji S, Ishii T (2009) Development and Operation of the Autonomous Mining Truck System. J Mmij (The Min Mater Process Inst Japan) 125:509–513
6. Costner KM, Gunther F, Brune J, Mischo H (2018) State of the art of the industrial internet of things and underground autonomous robots in the United States. In: SME Annual Meeting Preprints 19–147. Society for Mining, Metallurgy, and Exploration, Denver, CO, 1–3
7. Tamers SL, Streit J, Pana-Cryan R et al (2020) Envisioning the future of work to safeguard the safety, health, and well-being of the workforce: A perspective from the CDC's National Institute for Occupational Safety and Health. Am J Ind Med 63:1065–1084. https://doi.org/10.1002/ajim.23183
8. Schmidt D (2024) Bringing the mine to the city. In: North American Mining. https://northamericanmining.com/index.php/2024/03/27/bringing-the-mine-to-the-city/. Accessed 14 Jul 2025
9. Raube M (2024) Komatsu achieves major autonomous milestones. In: Komatsu. https://www.komatsu.com/en-us/newsroom/2024/komatsu-achieves-major-autonomous-milestones. Accessed 14 Jul 2025
10. Mining.com (2022) Caterpillar autonomously hauls more than 1 billion tonnes of material with Cat Command for hauling in less than a year, March 16. In: https://www.mining.com/web/caterpillar-autonomously-hauls-more-than-1-billion-tonnes-of-material-with-catcommand-for-hauling-in-less-than-a-year%EF%BF%BC
11. Goodbody A (2022) Komatsu emphasizes automation at MINExpo. Mining Magazine, September 15. In: https://www.mining

magazine.com/fleet/news/1417764/komatsu-emphasises-automation-at-minexpo
12. Jong EC, Luxbacher KD, Kirsch PA et al (2015) SME Annual Meeting Preprints 15–057. Society for Mining, Metallurgy, and Exploration, Denver, CO, 1–7
13. DOL MSHA (1997) Federal Mine Safety and Health Act of 1977. The United States Department of Labor (DOL), Mine Safety and Health Administration (MSHA), 200 Constitution Ave NW, Washington, DC 20210
14. MSHA (1985) 30 CFR Part 57 (up to date as of 4/04/2025), Safety and Health Standards—Underground Metal and Nonmetal Mines. US Mine Safety and Health Administration
15. CalderW, Snyder DP, Burr JF (2018) Intrinsically Safe Systems: Equivalency of International Standards Compared to U.S. Mining Approval Criteria. Katie Sullivan (ed.), IEEE Transactions on Industry Applications. Institute of Electrical and Electronics Engineers Inc., vol. 54, no. 3, pp 2975–2980. https://doi.org/10.1109/TIA.2018.2804322
16. Bouchard J, Sbarbaro D, Desbiens A (2018) Plant automation for energy-efficient mineral processing. K. Awuah-Offei (ed.), Energy Efficiency in the Minerals Industry, Green Energy and Technology. Springer, pp 233–250 https://doi.org/10.1007/978-3-319-54199-0_13
17. Olivier LE, Craig IK (2017) A Survey on the Degree of Automation in the Mineral Processing Industry. In: IEEE Africon 2017 Proceedings. IEEE, pp 404–409
18. Burgess-Limerick R (2020) Human-systems integration for the safe implementation of automation. Min Metall Explor 799–1806. https://doi.org/10.1007/s42461-020-00248-z/Published
19. Scopus (2025) TITLE-ABS-KEY (Autonomous Haulage Systems OR Autonomous Mining Truck Systems). https://www.scopus.com/pages/home?display=basic#basic. Accessed 16 Jul 2025
20. Scopus (2025) mining automation OR autonomous mining.https://www.scopus.com/results/results.uri?st1=%22Autonomous+Haulage+Systems%22+OR+%22Autonomous+Mining+Truck+Systems%22&st2=&s=TITLE-ABS-KEY%28%22mining+automation%22++OR++%22autonomous+mining%22%29&limit=10&origin=searchbasic&sort=plf-f&src=s&sot=b&sdt=b&sessionSearchId=117817414ca033566841e068c323bccd Accessed 15 Dec. 2025
21. Ralston JC, Hainsworth DW, Reid DC et al (2001) Recent advances in remote coal mining machine sensing, guidance, and teleoperation. Robotica 19:513–526. https://doi.org/10.1017/S0263574701003447
22. Dragt BJ, Camisani-Calzolari FR, Craig IK (2005) An overview of the automation of load-hual-dump vehicles in an underground mining environment. Pavel Zítek (ed.), 16th Triennial World Congress, Prague, Czech Republic. IFAC
23. Dunbabin M, Corke P (2006) Autonomous Excavation Using a Rope Shovel. Field Service Rob STAR 25:555–566
24. Meech J, Parreira J (2011) An interactive simulation model of human drivers to study autonomous haulage trucks. In: Procedia Computer Science. Elsevier B.V., pp 118–123
25. Parreira J, Meech Norman JB (2011) Autonomous Haulage Systems-Justification and Opportunity. In: Kamel M et al (eds) AIS 2011, LNAI. Springer-, Berlin Heidelberg, pp 63–72
26. McNab KL, Garcia-Vasquez M (2011) Autonomous and remote operation technologies in Australian mining. Prepared for CSIRO Minerals Down Under Flagship, Minerals Futures Cluster Collaboration, by the Centre for Social Responsibility in Mining. Sustainable Minerals Institute, The University of Queensland Brisbane
27. Dudley JJ, McAree PR (2013) Why the mining industry needs a reference architecture for automation initiatives. In: 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Wollongong, Australia, July 9–12. IEEE, p 1803
28. Beitler S, Holm M, Mozar A et al (2014) The data preparation for longwall workface automation with the shield-data based horizon control. In: International Multidisciplinary Scientific GeoConference, Section Exploration and Mining. SGEM, STEF92 Technology Ltd., pp 639–345
29. Ralston JC, Strange AD (2016) 3D robotic imaging of coal seam using ground penetrating radar technology. In: 2016 16th International Conference of Ground Penetrating Radar (GPR). IEEE
30. Anderson JM, Nidhi K, Stanley KD et al (2016) Autonomous vehicle technology: a guide for policymakers. Rand Corporation
31. Ruiz-Del-Solar J, Vallejos P, Asenjo R et al (2016) Robotics research in Chile: Addressing the needs of the local mining industry at the Advanced Mining Technology Center. Int J Adv Robot Syst 14. https://doi.org/10.1177/1729881416682695
32. CRO Forum (2017) Autonomous Machines. Emerging Risks Initiative – Position Paper
33. Bouchard J, Sbarbaro D, Desbiens A (2018) Plant automation for energy-efficient mineral processing. In: Awuah-Offei K (ed) Energy Efficiency in the Minerals Industry, Green Energy and Technology. Springer, pp 233–250
34. Frank M (2019) A step towards the design of collaborative autonomous machines: A study on construction and mining equipment. Department of Mechanical Engineering, Blekinge Institute of Technology, Sweden
35. Felsch WS Jr, Oliveira AF, Ortiz CEA (2019) Approach of mining equipment performance with simulation of the use of autonomous trucks. In: Mueller et al (eds) Mining Goes Digital. CRC Press / Taylor & Francis Group, pp 542–550
36. Peng SS, Du F, Cheng J, Li Y (2019) Automation in U.S. longwall coal mining: A state-of-the-art review. Int J Min Sci Technol 29:151–159
37. Androulakis V, Sottile J, Schafrik S, Agioutantis Z (2019) Elements of autonomous shuttle car operation in underground coal mines. In: 2019 IEEE Industry Applications Society Annual Meeting. IEEE
38. Beal C, Thomson A, Vinson C (2019) New Technology & Innovation. Report 2 - Autonomous Mining Equipment
39. Kansake BA, Kaba FA, Dumakor-Dupey NK, Arthur CK (2019) The future of mining in Ghana: Are stakeholders prepared for the adoption of autonomous mining systems? Resour Policy 63. https://doi.org/10.1016/j.resourpol.2019.101411
40. Ali D, Ur Rehman A (2020) Adoption of autonomous mining system in Pakistan – Policy, skillset, awareness and preparedness of stakeholders. Resour Policy 68. https://doi.org/10.1016/j.resourpol.2020.101796
41. Barbosa V, da SB GR, Campos PHA et al (2020) Analysis of mobile communication coverage and capacity for automation in open-pit mines. Springer Series in Geomechanics and Geoengineering. Springer, pp 262–270
42. Jang H, Topal E (2020) Transformation of the Australian mining industry and future prospects. Min Technology: Trans Inst Min Metall 129:120–134
43. Lung RF (2020) Automation and Digitization Potentials of Underground Mining Methods: A Comparative Analysis and Identification of Key Performance Indicators. Faculty of Geosciences, Geotechnics, and Mining, Sustainable Mining and Remediation Management. Technical University of Bergakademie Freiberg
44. Bołoz Ł, Biały W (2020) Automation and robotization of underground mining in Poland. Appl Sci (Switzerland) 10:1–14
45. Voronov Y, Voronov A, Makhambayev D (2020) Current state and development prospects of autonomous haulage at surface mines. In: E3S Web of Conferences. EDP Sciences
46. Burgess-Limerick R (2020) Human-Systems Integration for the Safe Implementation of Automation. Min Metall Explor 37:1799–1806. https://doi.org/10.1007/s42461-020-00248-z/Published

47. GaoY, Wang F-Y, Ai Y, Cao D (2020) Bridging the physical, the digital, and the social. IEEE Internet Things Magazine 2:8–9. https://doi.org/10.1109/MIOT.2019.8835418
48. PriceR, Cornelius M, Burnside L, Miller B (2020) Mine planning and selection of autonomous trucks. In: Topal, E. (eds) Proceedings of the 28th International Symposium on Mine Planning and Equipment Selection - MPES 2019. Springer Series in Geomechanics and Geoengineering. Springer, pp 203–212. https://doi.org/10.1007/978-3-030-33954-8_26
49. Ishimoto H, Hamada T (2020) Safety Concept and Architecture for Autonomous Haulage System in Mining. In: 37th International Symposium on Automation and Robotics in Construction (ISARC 2020). Online, pp 375–384
50. Paredes D, Fleming-Muñoz D (2021) Automation and robotics in mining: Jobs, income and inequality implications. Extractive Industries Soc 8:189–193
51. Gaber T, Jazouli Y, El, Eldesouky E, Ali A (2021) Autonomous haulage systems in the mining industry: Cybersecurity, communication and safety issues and challenges. Electronics (Switzerland) 10. https://doi.org/10.3390/electronics10111357
52. Moreau K, Laamanen C, Bose R et al (2021) Environmental impact improvements due to introducing automation into underground copper mines. Int J Min Sci Technol 31:1159–1167. https://doi.org/10.1016/j.ijmst.2021.11.009
53. GMG (2021) System Safety for Autonomous Mining: A White Paper to Increase Industry Knowledge and Enable Industry Collaboration on Applying a System Safety Approach to Autonomous Systems. Global Mining Guidelines Group
54. Benlaajili S, Moutaouakkil F, Chebak A (2021) Infrastructural requirements for the implementation of autonomous trucks in open-pit mines. In: E3S Web of Conferences. EDP Sciences
55. Peinsitt T (2021) Recent developments towards Autonomous Tunneling and Mining Machinery. In: The 2021 World Congress on Advances in Structural Engineering and Mechanics (ASEM21), GECE, Seoul, Korea, August 23–26, 2021
56. NguyenHAD, Ha QP (2021) Robotic autonomous systems for earthmoving equipment operating in volatile conditions and teaming capacity: a survey. Robotica https://doi.org/10.1017/xxxxx
57. Chirgwin P (2021) Skills development and training of future workers in mining automation control rooms. Computers Hum Behav Rep 4. https://doi.org/10.1016/j.chbr.2021.100115
58. Bathla G, Bhadane K, Singh RK et al (2022) Autonomous Vehicles and Intelligent Automation: Applications, Challenges, and Opportunities. Mobile Information Systems
59. Wu X, Li H, Wang B, Zhu M (2022) Review on Improvements to the Safety Level of Coal Mines by Applying Intelligent Coal Mining. Sustainability (Switzerland) 14
60. Olmedo NA, Lipsett MG, Yuen J, Milne C (2022) Towards Autonomous Tailings and Pit Lake Monitoring with Amphibious Robots. In: Proceedings of Mine Water Solutions, June 14–16, 2022, Vancouver, Canada
61. Leung R, Hill AJ, Melkumyan A (2023) Automation and Artificial Intelligence Technology in Surface Mining: A Brief Introduction to Open-Pit Operations in the Pilbara. IEEE Robot Autom Mag. https://doi.org/10.1109/MRA.2023.3328457
62. Cerna GEP, Hernandez JRC, Herazo JCM, Castillo AP (2023) Evaluation of the overall effectiveness (OEE) of autonomous transportation system (AHS) equipment and its impact on mine design. Open pit mine case study. In: Procedia Computer Science. Elsevier B.V., pp 468–473
63. Matsui K, Adan F, Angeloudis P (2024) Decentralised Motion Planning for Autonomous Mining Haulage Trucks using Prioritised Multi-Agent MPPI. In Petros Ioannou (eds) 17th IFAC Symposium on Control of Transportation Systems CTS 2024, IFAC-PapersOnLine. Elsevier B.V., pp 154–161 https://doi.org/10.1016/j.ifacol.2024.07.333
64. Shimaponda-Nawa M, Nwaila GT (2024) Integrated and intelligent remote operation centres (I2ROCs): Assessing the human–machine requirements for 21st century mining operations. Min Eng 207. https://doi.org/10.1016/j.mineng.2023.108565
65. Kokkinis A, Frantzis T, Skordis K et al (2024) Review of Automated Operations in Drilling and Mining. Machines 12
66. Long M, Schafrik S, Kolapo P et al (2024) Equipment and Operations Automation in Mining: A Review. Machines 12
67. Burgess-Limerick R, Horberry T, Lynas D et al (2025) Human Systems Integration for Mining Automation, First Edition. CRC Press, Taylor & Francis Group
68. Du H, Chan L, Tong J et al (2025) Industrial Progress of Robotic Automation in Mining Applications: A Survey. Min Metall Explor 42:537–556
69. Niu Q, Wang P (2025) Open-Pit Mine Autonomous Truck Dispatching: Many-Objective Joint Optimization Strategy Considering Uncertainties. Concurr Comput 37. https://doi.org/10.1002/cpe.70147
70. Lacoursière MS (2025) The social license to automate in the mining industry. Mineral Econ 38:413–424. https://doi.org/10.1007/s13563-025-00494-x
71. Sun Y, Zhang L, Liu J et al (2025) Autonomous Driving of Trackless Transport Vehicles: A Case Study in Underground Mines. Sensors 25. https://doi.org/10.3390/s25103189
72. PWC (2023) Transforming India's mining landscape with autonomous technology
73. Title 30 Mineral Resources Parts 1 to 199. Office of the Federal Register National Archives and Records Administration, Special Edition of the Federal GPO, Register (2024) U.S. Government Publishing Office, U.S. Superintendent of Documents, Washington, DC 20402–0001 1–836
74. LaTourrette T, Regan L (2022) Barriers to the Commercialization and Adoption of New Underground. Coal Mining Technologies in the U.S.
75. Krug A, Seidel P, Knoblinger T (2019) Autonomous machines in the fast lane? The path forward to autonomy in agriculture, construction and material handling
76. MSHA (2025) Code of Regulations, Title 30 C.F.R. (up to date as of 4/04/2025), Mineral Resources. US Mine Safety and Health Administration, accessed on 4/21/2025. https://www.ecfr.gov/current/title-30
77. FCC (2025) Code of Federal Regulations: Title 47. In: Federal Communications Commission. https://www.ecfr.gov/current/title-47#block-menu-block-4#block-menu-block-4. Accessed 15 Jul 2025
78. DMIRS (2014) Code of Practice for Safe Mobile Autonomous Mining in Western Australia
79. Government of Alberta (2019) Applying for Occupational Health and Safety Autonomous Haulage System Approval
80. ISO (2019) ISO 17757: Earth-moving machinery and mining —. Autonomous and semi-autonomous machine system safety
81. GMG (2019) Understanding the importance of functional safety for autonomous equipment. In: Retrieved from Global Mining Guidelines Group: https://gmggroup.org/importance-functional-safety-autonomous-equipment/
82. ISO (2010) ISO 12100: Safety of machinery — General principles for design — Risk assessment and risk reduction
83. MSHA DOL (2024) Testing, Evaluation, and Approval of Electric Motor-Driven Mine Equipment and Accessories. In: Mine Safety and Health Administration (MSHA), Department of Labor..https://www.federalregister.gov/documents/2024/12/10/2024-28315/testing-evaluation-and-approval-of-electric-motor-driven-mine-equipment-and-accessories

84. EMESRT (2006) Earth Moving Equipment Safety Roundtable. In: EMESRT. https://www.emesrt.org/
85. Lau CG, Haugh BA (2018) Megatrend Issues in Artificial Intelligence and Autonomous Systems
86. Joanne C (2023) Autonomy Scales Up in Mining. In: Inside Unmanned Systems. https://insideunmannedsystems.com/autonomy-scales-up-in-mining/
87. Gaokgorwe T (2023) The Application of Robotics in Deep Level Mining in South Africa and its Influence on Health and Safety. Master of Management (Digital Business), Faculty of Commerce, Law and Management. University of the Witwatersrand, Johannesburg
88. Sammler KG, House-Peters L (2023) Unblackboxing mediation in the digital mine. Geoforum 141. https://doi.org/10.1016/j.geoforum.2023.103745
89. kamble SJ, Katare LJ (2022) Autonomous Mining Truck Market Size, Share, Competitive Landscape and Trend Analysis Report, by Size, by Propulsion, by Level of Autonomy. Global Opportunity Analysis and Industry Forecast, by Type, pp 2025–2035