Industrial IoT in Mine Electrification:

Necessity or Luxury?

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Mining electrification, defined as the process of using electricity to power mine sites instead of fossil fuels, is one of the most significant and transformative trends in the mining industry of our time. It has direct impacts on the environment, social and governance (ESG), licence to operate, global competitiveness, and the ability to raise capital from investors and financiers. Recent industry efforts reflect the recognition of the importance of this trend by the mining industry.

However, successful electrification implementation cannot be achieved in isolation. It requires successful implementation of mining digitalisation in both the design and operation stages of an electrified mine. This is possible using the industrial internet of things (IIoT), a developing paradigm of interconnected "industrial things" equipped with embedded networking, sensors, and actuators. IIoT has the potential to revolutionise the mining industry by improving safety and efficiency and reducing costs through advanced sensors, data analytics, and predictive maintenance techniques.

Additionally, the integration of IIoT in the electrification and digitalisation of mining operations is a crucial step in achieving compliance with international and national regulations on reducing carbon emissions, such as those issued by the international council on mining and metals (ICMM) and the minerals council of Australia (MCA). Digital transformation of mines, explicitly focusing on implementing unmanned technologies, remote process control, and smart robots, cannot be achieved without IIoT devices. These technologies enable the mining industry to reduce labour costs, increase production, and improve safety by removing workers from potentially hazardous environments.

Mining digitalisation has its challenges that are summarised in Figure 1. As illustrated in this figure, the main challenges are associated with implementation cost, technical complexity, regulatory compliance, workforce training, and data management. Despite these challenges, the long-term benefits of increased productivity, reduced costs, and improved safety can outweigh these challenges.

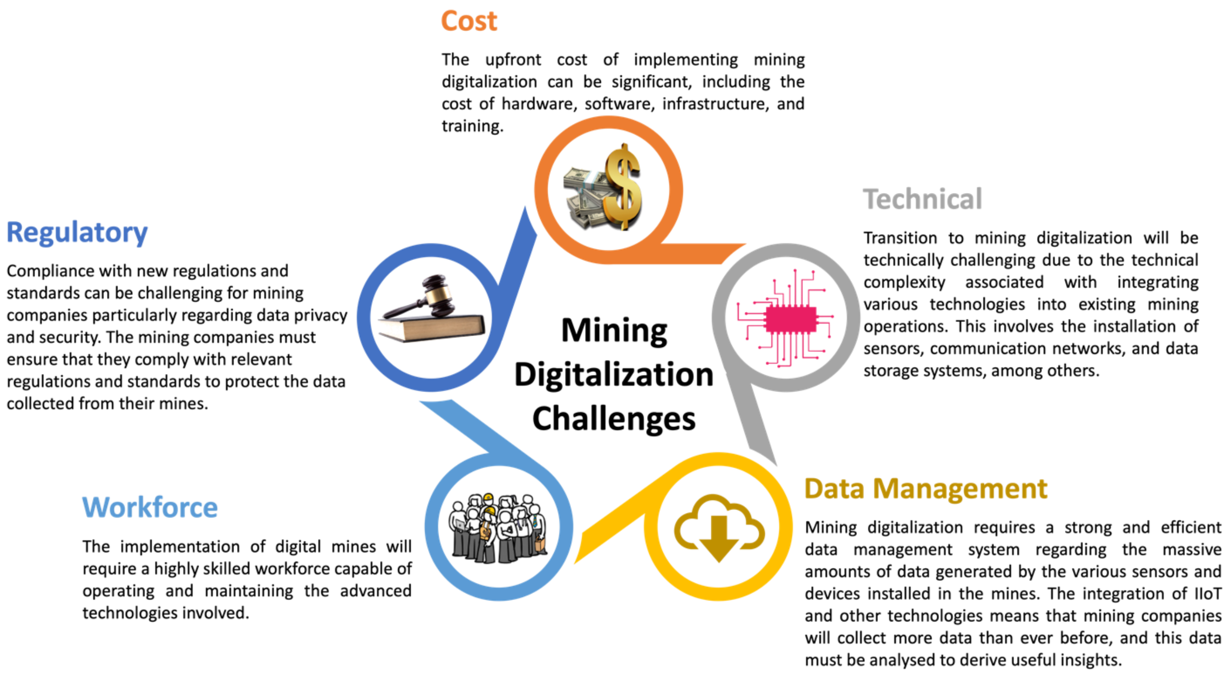


Figure 1. Mining digitalisation main challenges in a nutshell

This article discusses the necessity of mine electrification and how the deployment of IIoT can help achieve this goal. It defines IIoT, highlights key differences with commonly known IoT applications, provides an overview of industry initiatives, and presents use cases and further developments necessary to transition to mining electrification and digitalisation.

Section 1 – Industrial Internet of Things - What is it and what is not it?

The internet of things (IoT) is a term that has gained popularity in recent years. As a result, the IoT has been subject to misinterpretation and misunderstanding. For instance, some consider using the Internet for anything, such as web surfing and social media, to be IoT. Therefore, it is crucial to provide a clear and understandable, yet general definition of the IoT. Simply put, IoT means using the Internet for data exchange, processing, storing, and analysis by devices, either automatically or with the user's assistance. This differs from the current usage of the Internet, in which humans produce and consume most of the data.

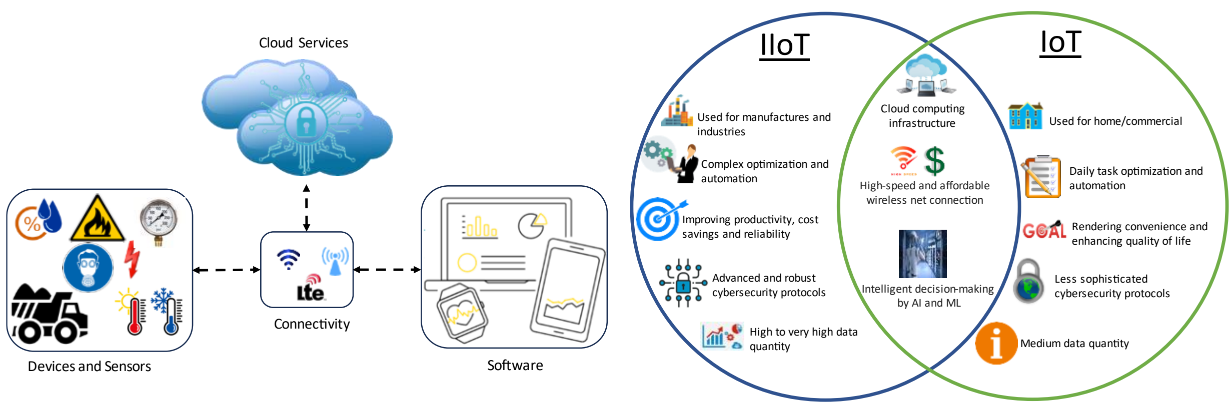
The term IoT was first coined by computer scientist Kevin Ashton in 1999. Only nine years later, in 2008, the number of connected devices through the IoT surpassed the world population. Today, the IoT is expanding into various sectors, such as public services, healthcare, smart buildings, smart cities, traffic management, precision agriculture, energy, and mines. According to the research conducted by IoT Analytics in 2022, the number of global IoT connections shows a significant growth of 100% between

2017 and 2021. Moreover, the global IoT market is expected to grow by at least 230% by the end of 2025.

According to a report by IoT Analytics, smart cities and IIoT are currently the top two IoT-based projects worldwide. IIoT, as a subset of IoT technology, involves the integration of complex industrial machinery with networked sensors, actuators, and software, allowing machine-to-machine (M2M) communications. The basic architectures of IoT and IIoT are similar and include four layers: IoT devices or sensors layer, connectivity layer, cloud service layer, and software or end user layers, as depicted in Figure 2.a.

Despite the similarity of IoT and IIoT in some respects, such as wireless networks, cloud computing, and the use of artificial intelligence (AI) and machine learning (ML), there are several major differences between these two, which are illustrated in Figure 2-b. The main differences are associated with their applications, goals, complexities, cybersecurity protocols, and data quantity. For example, in terms of goals, IIoT aims to optimise and improve productivity, efficiency, and reliability in industrial settings, leading to cost savings, improved quality control, and reduced downtime. However, the IoT aims to make daily life more convenient and connected, which does not necessarily provide significant cost savings and improve sustainability.

Additionally, IIoT solutions require even more robust and comprehensive cybersecurity measures due to the catastrophic consequences of cyberattacks for high-volume manufacturing processes, resulting in substantial production losses and financial setbacks. Furthermore, the result of an incorrect action in the control process can put the system into an unstable and unsafe condition. Hence, IIoT solutions incorporate sophisticated cybersecurity protocols that encompass secure and resilient system architectures, specialised chipsets, encryption, authentication, threat detection, and meticulous management processes.



(a) (b)

Figure 2. IoT vs IIoT systems: (a) general architecture, (b) differences

It is important to understand that IIoT is not just a technology solution. However, it is the best strategy for digital transformation of industries to improve the performance and productivity of industrial processes. Remote asset monitoring, control, and process automation are the three main use cases for IIoT. Other use cases include vehicle fleet management, location tracking, asset/plant performance optimisation, quality control and management, goods condition monitoring in transit, predictive maintenance, and on-site track and trace. The potential advantages of IIoT for the industry could be substantial. For example, ABB reports a 15% reduction in downtime and maintenance costs, 8% improved equipment performance and reliability, 25% extended asset lifespan, and 30% reduction in spare parts inventory cost due to IIoT integration into the industry.

Integrating IIoT is deemed crucial in achieving the full benefits of mining electrification in the mining industry. For example, a typical electric mine includes critical assets, such as electric trucks with onboard battery systems, that must be continuously monitored and controlled through a large number of sensors that generate massive data. With IIoT, these data can be stored, shared, combined, and analysed automatically to improve performance proactively by monitoring the system, identifying failures and maintenance, and eliminating bottlenecks. It can also be used for future planning and optimising the operation of machinery and equipment in real time in an adaptive way. Moreover, IIoT enables digital twining, which can be used to train the workforce, optimise industrial processes, and enhance safety.

Before delving into the necessity of IIoT for mining electrification, we briefly explain the current state of mine electrification efforts in the next session.

Section 2 – Ongoing Efforts in Mine Electrification

Mining electrification is one of the most significant and transformative trends in the mining industry. In 2021, the State of Play organisation released a survey report on mining electrification and its challenges and opportunities. This survey consists of more than 450 individual surveys, interviews with top mining executives, webinars, and workshops with identified mine companies and leaders. According to this survey, 89% of the mine managers in the world believed that existing mines would be fully electrified in 20 years and that the next generation of mines would be fully electric. Furthermore, this survey reveals that the economic, health, and environmental opportunities of mine electrification are enormous, but not without any challenges.

The main benefits of electrified mines are lower environmental impact, improved safety and health, and lower operational costs compared to diesel mining. For example, diesel machinery in mines produces pollutants and heat that need to be ventilated at a high cost. Moreover, they produce high levels of noise due to internal combustion engines and many mechanical moving parts. On the contrary, electric vehicles and stationary equipment are much quieter and cleaner, significantly improving miners' health and safety. Also, electric mines have less operating costs than traditional underground mines due to fewer ventilation requirements and CO_2 emissions.

The electrification of mines does, however, face several challenges. One of the main challenges is the high upfront cost of mining electrification. Generally, electric vehicles (EVs) in mining, such as energy-intensive haul tracks, are more expensive to manufacture than conventional vehicles due to the cost of the battery units. However, prices are decreasing as technology advances and some governments offer incentives to encourage mining companies to electrify their operations. Moreover, the battery recharging time and its impact on mining productivity, charging infrastructure design and operation, and onboard battery life are among the main challenges that require research and development to be adequately addressed.

Section 3 – Industrial IoT in Electrification and Digitalisation of Mining

The realisation of the benefits of mining electrification cannot be imagined without digitalisation, hence the IIoT. That is the main reason behind the industry's ambitious goals to integrate IIoT into their operation. IIoT is expected to enhance the reliability, efficiency, safety/health, and cost effectiveness of the mining operation and downstream processes. Key technologies that will be used in IIoT-enabled mines include automation, robotics, remote operation, smart sensors/real-time data capture, analytics, artificial intelligence (AI)/machine learning (ML), and digital twinning. Some of the major IIoT projects implemented by the mining industry in recent years are summarised below, demonstrating the profound and extensive scope of endeavours in this area:

- Rio Tinto is one of the major mining companies with ambitious net-zero emission targets in the industry. Their `Mine of the Future' program is specifically designed as a part of the company's electrification roadmap. The program is built on a full IIoT architecture. Rio Tinto's 'intelligent mine' is fully autonomous and uses a network of sensors, cameras, and other IoT devices to gather data on everything from equipment performance to environmental conditions. This data is fed into a central analytics platform that uses ML algorithms to identify patterns and predict future performance. Intelligent mining is just part of the overall IIoT architecture used in the Mine of the Future program. It also includes a digital twin (DT) asset that enables team members to visually navigate the asset, plan their work, and provide virtual reality training to the workforce. Figure 3 summarises the main innovative ideas integrated with this program.

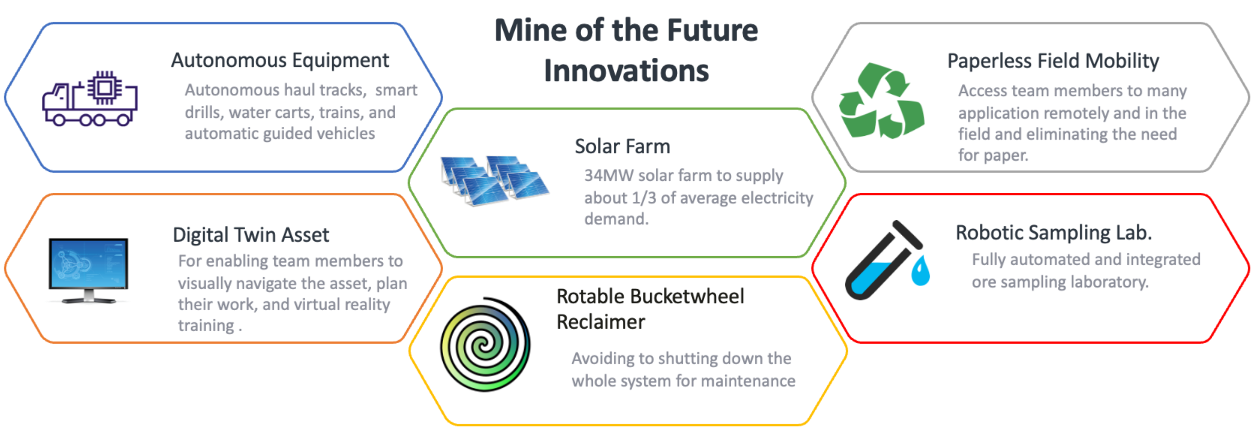


Figure 3. Innovations of Rio Tinto's Mine of the Future program

Rio Tinto has significantly improved its mining productivity, efficiency, and safety using the `Mine of the Future' program. For example, the company has reported 24/7 operation of autonomous trucks without breaks, leading to a 15% increase in productivity and a 10% reduction in fuel consumption. Rio Tinto has also reported significant safety improvements, with a 50% reduction in vehicle-related accidents and a 90% reduction in incidents that could cause severe harm or fatalities.

- The Swedish company Boliden is another mining company that, in collaboration with ABB, started using IIoT in one of its electrified mines by relying on a range of connected devices and sensors, including EVs, charging stations, and energy storage systems. The mining trucks, loaders, and other equipment used in operation are powered by electricity generated on-site through a combination of renewable energy sources, e.g., wind and solar power, and traditional power sources, such as diesel generators. The mine also uses analytical tools to forecast energy demand and optimise energy storage systems to minimise energy consumption.

- The Syama Gold Mine in Mali, owned and operated by Resolute Mining, is Africa's first fully automated mine. This intelligent mine was built on an IIoT architecture that utilises partly electric and autonomous trucks, drills, and loaders. This underground mine was also enhanced with super-fast fibre optic and wireless network connections that enable remote control actions. Syama also uses a three-dimensional (3D) mine visualiser system that provides workers with a real-time 3D model of the entire mining environment. In addition to the 3D visualiser, the mine is equipped with an IoT-based system optimiser to efficiently plan future mining activities and operations. Moreover, this mine is powered by a hybrid system, including a solar PV farm, battery storage, and diesel generators, significantly reducing emissions.

The implementation of IIoT in electrified mines can be characterised by a specific architecture model, as illustrated in Figure 4. Geologically, this architecture can be divided into two distinct parts: on-site, located at the mine site, and off-site, located in the cloud.

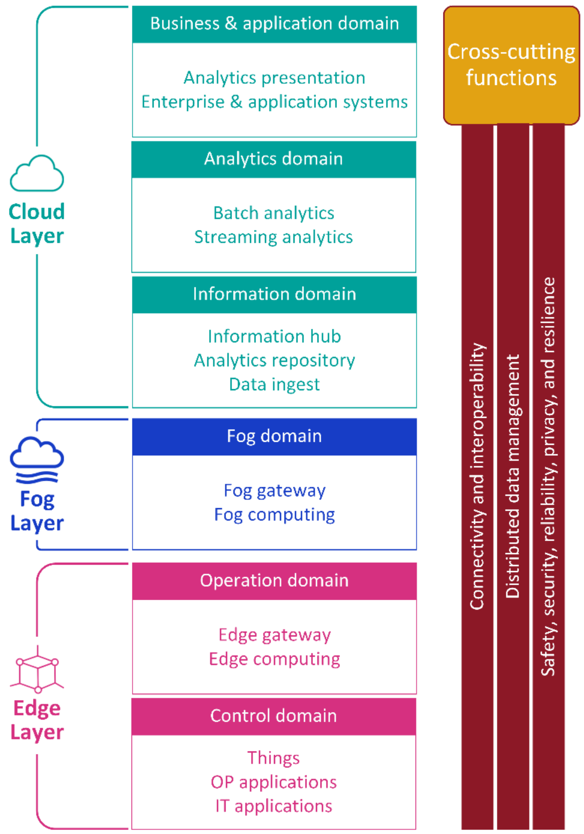


Figure 4. IIoT architecture for electrified mines

The on-site part of the architecture includes the Edge and Fog Layers, which are essential for local control and automation. The Edge control domain comprises various mine components, such as sensors, actuators, devices, and other physical systems. This layer is responsible for collecting data from three primary sources: 1) Things, which are physical sensors with built-in microprocessors and communication links; 2) operational technology applications, including control and automation systems such as programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) systems; and 3) information technology (IT) applications, including data from transactional IT systems and other nonstructured data. The monitoring and control system of the electric mining equipment is a good example of this layer.

The Edge operation domain manages and operates the control domain, including tasks such as asset deployment and management, monitoring and diagnosis, optimisation, and prognostics. The edge gateway is responsible for data collection and filtering, running some basic data analytics in real-time, data storage, and data exchange with sources in its area and the Fog layer. Edge computing is the most challenging function of this domain, as it requires processing large amounts of data in real-time. The EV motor's optimisation system is a practical example of edge computing in an electrified mine.

The Fog Layer is an on-premise gateway that collects data from several edge devices and gateways, performing higher-level processing and analysis—this layer filters, analyses, processes, and stores data for transmission to the cloud.

The top layers of the architecture are typically located in the cloud, but depending on the use case, they can be located partially or fully on-site. The information domain is responsible for the management, grouping, and repositories of data that the upper layers will use. It includes three main functions: Data Ingest, responsible for obtaining and importing data into an Analytics Repository; Analysis Repository, responsible for collecting and organising data from multiple sources; and Information Hub (Semantic Layer), which helps people understand and use the stored data, which is important for business analysis.

The Analytics Domain is responsible for analysing historical and real-time data. This layer enables the study of all kinds of data using sophisticated methods, such as predictive data mining, neural networks, complex event processing, and cognitive techniques, to produce information that increases operational efficiency and accelerates decision-making. It also enables the discovery of deeper insights, predictions, and the creation of recommendations.

The Business and Application Domain uses data from the Information Domain (Information Hub and Analytics Repository) or interactive output from the Analytics Domain for report generation and dashboards. This is a technical environment for the execution of practical enterprise and application logic, including enterprise resource planning (ERP), customer relationship management (CRM), human resource management (HRM), manufacturing execution systems (MES), billing, and analytics presentation (report, dashboard).

Furthermore, some functions are used and thus distributed across all layers, including Connectivity and Interoperability, distributed data management (DDM), and safety, security, reliability, privacy, and resilience. The first function ensures that different parts of the systems and layers can communicate with each other properly. DDM is responsible for reliable storage and scalable archiving. The other function is responsible for human safety, confidentiality, integrity, and availability (CIA), overall system reliability, data access restrictions, and handling dynamic adversarial situations. An example in cybersecurity is where cybercriminals are constantly evolving their methods to breach a network's defences, while cybersecurity professionals are simultaneously developing new security measures to thwart those attacks.

Section 4 – Industrial IoT Requirements for Mining Electrification

The IIoT can be used in mines, especially electric mines, to improve key performance indices (KPIs), which are a set of indices to monitor and measure the performance of the mining operation. For example, IIoT sensors can be installed on electric mining equipment and vehicles to collect data on energy consumption, payload, temperatures, motor load and speed, and other operational indicators. This data can then be analysed in real time or offline to identify patterns and trends that can be used to optimise equipment performance and reduce downtime. However, some requirements must be characterised to realise the benefits of IIoT in an electric mining setting.

Subsection 4.1 - Electric mining vehicles and equipment

The use of EVs and electric equipment in the mining industry has become increasingly prevalent, thanks to advances in battery technologies, power electronics, digitalisation, and automation. EVs and electric equipment are crucial in improving efficiency and reducing environmental impact, including greenhouse gas emissions and diesel particulate matters (DPMs). Some of the most common types of electric machinery found in the mining industry, whether battery-powered or tethered cable, are electric rope shovels, electric load-haul-dump (eLHD) trucks, electric haul trucks, electric drills, electric service vehicles, electric crushers, electric scoops, boomers, and smaller trucks, electric locomotives, battery-electric explosives chargers, rock bolting rigs, and conveyors.

The IoT has already proven itself to smooth the transition to an electrified transportation system. Previous studies reveal that the IoT increases the overall performance and safety of light-duty electric vehicles through real-time battery management, autonomous driving, preventive maintenance and alerting, and speed control. For example, IoT technology can indirectly address the range anxiety problem, a significant barrier in transportation electrification, by monitoring and analysing real-time data such as battery, charging infrastructure distance, and EV speed control. With that being said, we should note that mining EVs differ from other EV types, owing to challenging environmental conditions, the heavy loads, and the need for high reliability and safety to meet site productivity targets. IIoT can help address these challenges by providing real-time data and analytics to optimise performance and minimise downtime. In particular, IIoT can provide valuable insights into the operation of electric motors/generators, batteries, chargers, and regenerative braking, as shown in Figure 5, which can be used for preventive maintenance and operation optimisation. As an example, IIoT can improve the efficiency of regenerative braking and optimise the utilisation of stored battery power by collecting real-time inputs from multiple sensors, including wheel speed, brake pedal position, battery state of charge, motor, battery status, and other vehicle-related inputs to predict the required braking force for the vehicle, managing torque demand in the vehicle, and determining the brake status.

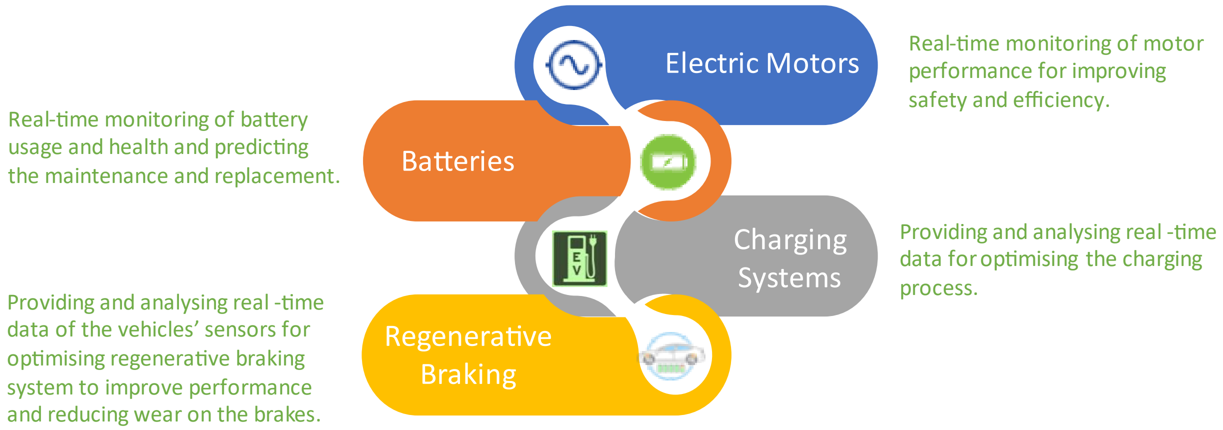


Figure 5. IIoT benefits for electric vehicles and equipment

The IIoT infrastructure used for mining EVs can be centralised or decentralised. In a centralised system, all sensor data from mining EVs is transmitted to a central hub for analysis and decision making. This centralisation provides a holistic view of the entire mining operation, offering valuable insights into the interactions among different vehicle components. This approach tends to have better security controls in place as all data is stored in one location. However, it may come with challenges, such as scalability issues, higher costs, and susceptibility to single point failure.

On the other hand, a decentralised system enables each mining EV in the IIoT network to have a dedicated set of sensors and analytics tools. This approach allows real-time data analysis and decision making at the vehicle level, reducing the dependency on centralised control. Decentralised systems are often more cost-effective, flexible and resilient, as they mitigate the risk of a single point of failure and adapt well to various scenarios. However, they can be more complex to manage due to data dispersion across multiple locations and systems.

Practical applications often strike a balance between the two frameworks by combining elements of both centralised (cloud) and decentralised (edge) systems. This hybrid approach optimises data collection, analysis, and decision making while addressing the specific needs and challenges of mining vehicles in the IIoT ecosystem.

Subsection 4.2 – Mine sensors and actuators

Mining operations are heavily relying on advanced IIoT-based sensors to monitor and optimise the performance of various vehicles and equipment. According to a recent study published in the Mining Technology journal, some fundamental technical indicators must be monitored to ensure the safe and efficient operation of traditional mining equipment.

Mining EVs and equipment use various sensors and actuators to monitor and control their performance. Position, temperature, location, light, pressure, and proximity sensors are a few examples of sensors used in electrified mines. These sensors are critical in ensuring EVs' safe and efficient operation. They provide real-time data to the control system, which can then optimise performance and prevent damage to the components.

Other types of sensors are also commonly used in mining operations to monitor various parameters, including ventilation fan speed, pump water level, power status, and conveyor belt conditions, such as speed and slip detection. Environmental mine sensors also play a crucial role, with gas sensors used to detect methane, oxygen, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO). Other environmental sensors include airflow, temperature, humidity, vibration, and smoke.

Subsection 4.3 – Wireless networking technologies

IIoT relies on various networking technologies to connect devices and enable communication. These technologies can be broadly categorised into three groups based on their range: wide area networks (WANs), local area networks (LANs), and personal area networks (PANs).

WANs, such as 3G, 4G, 5G, NB-IoT, and LoraWAN, are designed for long-range communication and are typically used in applications where devices are widely dispersed. LANs, such as WiFi, are meant for shorter-range communication and are typically used in settings where devices are close to each other. PANs, such as Bluetooth, ZigBee, infrared, and RFID, are used for very short-range communication and are typically used to connect devices near each other.

Table 1 compares these technologies based on various parameters, such as communication range, data rate, network capacity, power consumption, complexity, latency, and underground penetration.

Table 1 Communication technologies

	ZigBee	WiFi	BLE	LoRa	NB-IoT	4G/5G
Communication range (m)	50-100	50-100	10	10-20K	5-15K	5-30K
Typical data rate (Mbps)	0.25	150	1	0.0384	0.1	100
Network capacity (nodes)	65K	100	7	1000	A few K	A few K
Power consumption (mW)	Average	High	Low	Very Low	Very Low	Very High
Complexity	Low	High	High	Low	Low	Low
Latency	Low	Average	Low	High	High	Very High
Underground penetration	No	No	No	Yes	Yes	No

Bluetooth low energy (BLE) is a low-power wireless protocol commonly used in consumer electronics and for connecting devices near each other. BLE can be used in electric mines for asset tracking, inventory management, and monitoring and controlling ventilation systems. It can also be used for wireless monitoring of a single machine, such as the electric motor/generator of the EV. However, it has limited use cases due to its low network capacity of seven nodes.

ZigBee is a low-power wireless protocol ideal for applications requiring low data rates and long battery life. In future electric mines, ZigBee can be used for wireless monitoring of equipment and environmental conditions, such as temperature, humidity, and air quality. It can also be used to control and manage lighting systems in the mine. The deterministic version of Zigbee is a good candidate for the EV sensor network.

WiFi is a widely used wireless communication protocol that offers high bandwidth and range. Still, it is not suitable for energy-limited applications, because of its high data rate and power consumption. In electric mining, WiFi can be used for real-time video monitoring of underground operations and data transmission between equipment and sensors. It can also be used for employee communication and location tracking. WiFi is commonly used in autonomous haulage systems (AHS) and vehicles.

Long-range (LoRa) is a low-power, long-range, and low-cost wireless communication protocol. We could use LoRa to track and monitor mobile equipment, such as trucks, in an electric mine. It can also be used for environmental condition monitoring and remote control of equipment. LoRa is well suited for underground mining applications due to its deep-penetration capabilities, recently validated by a team of researchers at the University of New South Wales (UNSW). A single LoRa gateway can easily cover about 1000 devices in a range of a few kilometres.

On the other hand, narrow-band IoT (NB-IoT) technology uses existing cellular network infrastructure to provide low-power and low-cost communication. In future electric mining, NB-IoT can be used for real-time tracking and monitoring of assets, such as equipment and personnel. It can also be used for remote control of equipment and sensors. Ideally, it works for underground mines. For instance, in a recent pilot study, NB-IoT could access devices located up to 400m underground with an on-land cellular coverage range of 700m. Although LoRa and NB-IoT have limited data rates and relatively high latencies, they suit many monitoring applications in an electric mine.

Cellular communications (4G/5G) is widely used in IoT applications due to its simplicity, high-speed data transmission, low latency, and broad coverage. In electric mining, we could use it for real-time monitoring of operations and transmitting data between different equipment and sensors. It can also be used for employee communication and location tracking. However, cellular technology is not well suited for energy restricted scenarios or underground applications due to its high power consumption and poor connectivity in underground environments.

Subsection 4.4 - Mining data analytics

Data analysis is the process of uncovering patterns and insights in large sets of data to transform that data into valuable business insights. Data analysis can improve efficiency, safety, and risk management in the mining industry by monitoring trends, identifying abnormalities, and analysing data from connected assets. According to studies, integrating data analytics into the mining industry can result in an increase of up to 40% in productivity. According to another study by IoT Analytics, the top three industrial use cases for data analytics are predictive maintenance, quality inspection and assurance, and optimisation of manufacturing processes. A report by Schneider Electric also found that data-driven optimisation can lead to 50% cost savings, 20% reductions in time to market and 50% increases in productivity. However, a significant portion (over 80%) of data generated in industries goes unused, and a higher percentage will not be analysed at all.

Analysing data from IIoT devices in the context of the mining industry involves a structured sequence of steps, as illustrated in Figure 6. These processes include collecting data in various formats and frequencies, transforming and enriching data with external sources, storing data as time series for analysis, running SQL queries and applying ML techniques for prediction, and building analytics and reports for various applications. For instance, in an electric mining setting, sensors embedded in mining equipment, such as electric haul trucks and drills, continuously gather data on equipment health, power consumption, and environmental conditions. This data is then processed and analysed through the IIoT infrastructure to predict maintenance needs, optimise energy usage, and enhance overall operational efficiency.

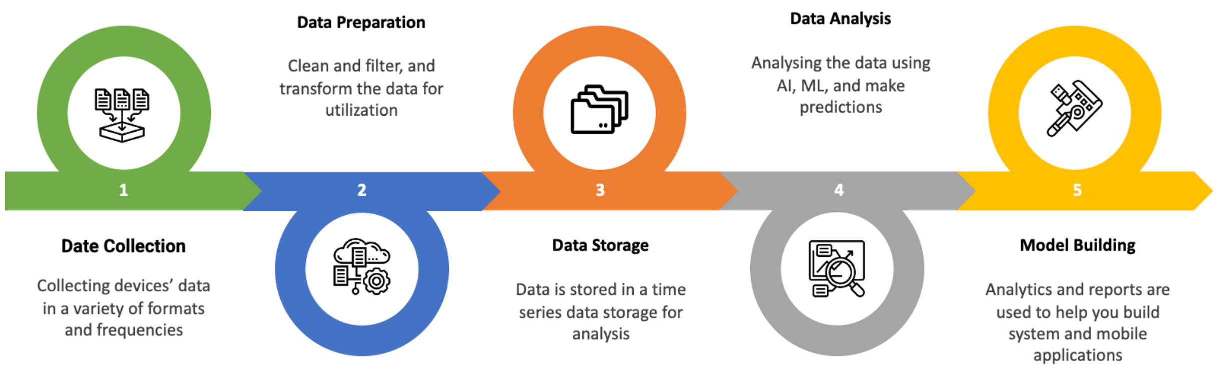


Figure 6. IIoT analytics steps

In the mining sector, data analysis can be assumed to take three distinct forms: descriptive, predictive, and prescriptive. Descriptive analysis involves rapid comprehension of collected data through the aggregation of information and the computation of fundamental statistics, often presented visually. For example, in an electric mine, descriptive analysis could involve summarising data from sensors installed on electric shovels to quickly assess their performance and energy consumption patterns.

Predictive analysis delves into the modelling and forecasting of future data and behaviours by scrutinising historical data, which includes classification and anomaly detection within time-series data. In an electric mine, predictive analysis could involve using historical data from electric drilling equipment to predict potential equipment failures and schedule maintenance proactively, thereby reducing downtime and operational disruptions.

Lastly, prescriptive analysis focuses on enhancing data-driven decision-making processes, ultimately optimising operational outcomes in the dynamic environment of mining, especially in the context of IIoT applications in electric mining settings. For example, prescriptive analysis may involve recommending adjustments to the charging schedules for electric mining vehicles to minimise energy costs and reduce peak demand on the electrical grid, thereby improving cost-efficiency and grid stability.

Subsection 4.5 – Autonomous Operation and Digital Twin

The future of the mining industry cannot be imagined without autonomous equipment due to their higher safety, productivity, and environmental friendliness. For this reason, most mining companies, such as BHP, Rio Tinto, FMG, and Roy Hill, have started operating autonomously, at least partially using remote control systems. The global market size for mining automation increased by 50% compared to 2017 and reached $3.2 billion in early 2023.

It is well-known that digital twin technologies are the steppingstones for transitioning industries towards autonomous operations. In this context, a digital twin consists of three parts: 1) an object in the physical environment; 2) a virtual copy of that object in a computer space; and 3) a real-time information and data exchange link for binding the real and virtual conditions of the object. In general, the use of digital twin in mining has the potential to transform the industry by enabling more efficient, sustainable, and profitable mining operations. In particular, a digital twin of a mining operation is a virtual replica of a physical mining setting that allows decision-makers to simulate and evaluate different processes and make data-driven decisions. By combining real-time sensors data with historical data, mining companies can easily monitor and analyse their performance in the digital twin. They can continuously forecast operational performance and equipment health and predict how a system can be automatically adjusted in critical situations. This can help prevent unexpected failures and operational issues before they occur. Moreover, they can simulate and test various operation scenarios before implementing them in the real world to optimise and improve the efficiency and safety of the new solutions. Besides, a digital twin mixed with virtual reality (VR) is an advanced tool for training the mining workforce in a safe and reliable environment.

Building digital twin and autonomous systems in the mining sector could be done easier with electrified vehicles and machinery than with diesel-operated ones. The main reason is that digital twin and automation require a fast, accurate, and large amount of data exchange collected from various parts of the system and operation, and on-the-fly analytics, which can only be provided by IIoT technology. Moreover, the decision-making process and actions taken should be fast enough to respond to changes coming from control systems and the digital twin, which can be achieved easier through electronic sensors, actuators, and machinery. MacLean Engineering, for instance, has aimed to create a digital twin for its mining vehicles to improve its customers' machine analysis and performance. Their IntelliOp vehicle management system (VMS) provides real-time analytics for its EV fleet at the Borden gold mine, Canada.

Subsection 4.6 - Predictive maintenance

Predictive maintenance (PdM) is a powerful use case of data analytics using a vast amount of data and ML techniques to anticipate potential issues and prevent them from escalating into costly failures. The practice of PdM can be applied in various industries, including mining, where it can be used to optimise equipment performance, increase efficiency, and reduce unplanned downtime.

PdM can be applied in fleet management, particularly in underground mining. For instance, using data from LHD trucks to predict failure is a well-researched field. A typical LHD has more than 150 sensors. In one study, an ML method was used to classify the engine condition of a diesel LHD truck into three categories (normal, suboptimal, or imminent failure), considering engine data, including torque, coolant temperature, oil pressure, turbo boost pressure, and speed. In another study by Dingo, a provider of PdM solution, a half million dollars savings and a 30% reduction in the total number of engine, brake and suspension failures were reported using an IIoT asset health monitoring system for haul trucks. Other commercially available solutions are Komatsu's Smart Construction, Caterpillar's MineStar Health, and ABB's Ability Asset Vista Condition Monitoring.

The use of AI-based pdM for EVs is mainly in the research stage. However, with the increasing use of EVs in the mining industry, they will soon be commercialised. Examples of fault diagnosis in electric motors include predicting the remaining useful life (RUL) of the motor's rotary bearings and capacitors, detecting vibration heteroscedasticity, fault detection and diagnosis for regenerative braking systems, and monitoring induction motors. The EV battery is also a major research focus, with studies aimed at localising faulty cells, predicting RUL, estimating state-of-health (SoH), and detecting external short circuits. However, most of these studies focus on conventional EVs, and more research is needed for mining EVs. As a practical use case, Goldcorp's Borden Mine in Ontario, Canada, uses a PdM program to monitor the health of its EVs. The program uses sensors to track vehicle temperature, vibration, and other key parameters. By analysing the data in real time, the mine can identify potential problems before they become serious problems, avoiding excessive downtime and maintenance costs.

Conclusions

The integration of IIoT in mining electrification and digitalisation can significantly improve the efficiency and safety of mining operations. IIoT technologies, such as sensors and networking technologies, enable real-time monitoring and analysis of mining KPIs and enhance the performance of mining electric machinery through predictive maintenance. However, implementing IIoT in mining operation requires special considerations for interoperability, scalability, security, and safety. In addition to the high upfront cost of hardware, technologies, infrastructure, and implementation, close collaboration between government agencies, mining companies, OEMs, and research institutions would be essential to successfully implement and scale IIoT in mining.

One potential research direction could be the development of PdM algorithms for mine operation using IIoT technology. As one of the major use cases for IIoT in mining, PdMs can help analyse data from mining equipment to predict when it is likely to fail, allowing for proactive maintenance and reducing downtime. Another potential research direction could be the integration of AI and ML into mining data analysis to improve the speed, accuracy, and efficiency of decision making in mining operations. Additionally, data mining approaches are needed to gain insights from the immense data stream of thousands of IIoT sensors in the field.

In addition, research and engineering work is required to address open challenges, such as interoperability and integration, scalability, flexibility, security and safety, mobility management, virtualisation at the edge, centralised to distributed systems of systems, and digital twins. It is also essential to explore the availability of IIoT cloud providers to meet the increasing data storage and management demands of mining operations. By addressing these research areas, the industry can unlock the full potential of IIoT in mining electrification and digitalisation and achieve sustainable and safe mining operations.

For Further Reading

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