Status of Mine Electrification and Future Potentials

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Abstract-

The electrification of mining operations is rapidly emerging as a central issue for the resources sector and its efforts to improve reliability and health/safety, and to reduce cost. The reliance on fossil fuel and gas generated electricity is a significant proportion of current mining operational costs and the prevalence of diesel fuel usage is a significant health and safety concern. The use of electric vehicles and machinery combined with partial or stand-alone renewable energy powered microgrids provides a pathway to more efficient, sustainable and safer mining operations, both for underground mining and open-pit mining. Electrification also presents an opportunity to integrate Internet of Things (IoT) technologies such as autonomous vehicles, communications networks and data analysis for safety and higher efficiency. Digitalization and automation is also the solution to reduce operational costs in areas related with concentration and transport. The transition to an electric mining future is complex and will require substantial investment in infrastructure, technologies, and hardware as well as collaboration between the mine operators and service industries, research organisations and regional, State and Federal governments, and newly skilled workforce in Australia. This paper provides an overview of the status of mine electrification and highlights the potential research directions, which aimed to help shape the resource industries transition to an electric and renewables mining future.

Keywords:
Mine electrification, mine electric vehicles, microgrids

I. Introduction

There is a synergy between the grid transformation in domestic/industrial power networks and mining power networks, which is likely to produce a greater combined effect specifically in Australia. The integration of distributed energy technologies, electric vehicles and energy management systems for the off-grid or the fringe of grid networks are very similar to the networks servicing regional and remote mine sites.

Moreover, the microgrid concept has provided a pathway to achieve reliable electricity networks [1] by quickly responding to the generation and demand imbalance and possibly by integrating localised charging points for electric vehicles (EVs) in the near future. The same concept has been imitated in various mining sites to transition towards more-electric and all-electric mining with an ideal target to utilise 100% renewable resources.

Technology readiness, successful demonstrations and industry acceptance are the primary reasons for such developments. Other factors are the cost of mining and safety. For example, ventilation, heating and refrigeration costs take up a large portion of operating costs in underground mining, which is primarily caused by the operation of diesel vehicles in mines.

When battery EVs are utilised (reducing emissions and minimizes environmental impacts), significant energy saving is also expected on ventilation and cooling systems. For instance, a study shows that an energy saving of 40% in ventilation and 30% in cooling can be achieved in a mine at Onaping Depth, Canada, by transportation electrification [2].

Furthermore, unlike the electrical cable-tied systems (in the form of overhead or underground), battery-powered machinery increases safety while reducing the risk of flashover and electrocution in harsh mining environment. Moreover, impact of diesel particulate matter (DPM) on human health can be completely eliminated by using EVs.

Opportunity for improvements to mining site electricity grids are envisaged by the emergence of new batteries, hydrogen/fuel cells, autonomous mining machinery, the integration of Internet of Things (IoT), Internet of Energy (IoE) and data mining, and by analysis applied to the mining process. Enhanced productivity and greater efficiency and performance are by-products of these improvements.

Although the above improvements can easily be foreseen, there are numerous unique characteristics and challenges in mining applications that still need to be carefully investigated. For example, electric haul trucks are used in mining for ore transportation usually in difficult geological conditions with more stringent safety issues than conventional transportation.

The unique characteristics and challenges in mining can be listed as below.

- Continuously evolving mining sites, electric grid and production practices due to the changes in landscape as a result of ore production;
- Additional safety requirements of employees and environmental impacts;
- Types of mining: surface or underground;
- Small margins in low grade ore-bodies;
- Energy-intensive production;
- Reduced reliability of supply due to grid connection, and susceptibility of the distribution lines to environmental conditions;
- Large variability and unpredictability of electrical loads;
- Availability, accessibility and sustainability of energy resources (gas, petrol, renewables) in mining sites;
- Harshness of the environment and altering landscape;

In the light of the aforementioned characteristics, the major factors that drive and accelerate mining electrification are classified in Table 1. This table also highlights mining electric vehicles and their benefits, worldwide mining microgrid examples and potential research directions.

Table 1. Factors that drive mining electrification.

Factors	Key Remarks
Greater energy consumption and high cost	• Ventilation energy: for cooling and removing hazardous gasses in underground mining, which can be as high as 70% of the total operation cost. • The deeper the mine, the higher the ventilation and cooling cost. • While specific energy of batteries is much less than fuel (13 kWh/kg versus ~250 kWh/kg), electric trucks use 1/4 of energy per tonne hauled compared to diesel trucks. • Between 30-50% of a mine's total energy use is the diesel for haul trucks.
Poor reliability/ power quality, and high mitigation cost	• If not off-grid, dependent on the reliability of the main grid. • Blackouts have a detrimental impact on mining process especially in smelters. • Additional transmission line, upgrade and grid improvement systems (SVCs and STATCOMs). • Frequent power quality problems due to starting and load characteristics of mining machinery, which also means higher health risk and poor reliability.
Health, safety and environ. issues	• Significant emissions (DPM) and heat in diesel eng. • Combustion engines have a serious health issues in underground mining • Electric equipment/processes and vehicles offer cost savings in ventilation, fuel, consumables (such as respirators), regulation checks and maintenance.
High maintenance cost	• Internal combustion vehicles are complex and require high maintenance and highly skilled mechanics.
Changes of infrastructure and high cost	• Mine sites are usually remote with varying terrain, which changes with ore production. • Support system and energy supply should adapt to topographical changes of the mine site including electric substations, lines/cables, transformers, rails, and supply links. • High costs of the adaptive measures and trolley assist systems (which require an overhead cable with the infrastructure cost per truck that is about 75% of the total truck price).
Poor productivity	• Conventional mining machinery is not suitable for timely integration into the mining process, and monitoring of EVs (such as for state of charge and range) can improve the productivity. • Difficulties and high cost of fuel transportation and storage in remote locations

II. Benefits of Mining Electric Vehicles

As stated above 30-50% of the total mine's energy usage is related to diesel used by the major mining vehicles that have a number of undesirable characteristics, which are likely disappear from the domestic market within the next few decades. To justify the uptake of EVs, a comparison of diesel and mining EVs is done in Table 2. Note that Epiroc offers "Batteries-as-a-Service" to speed customer acceptance of electrical replacements for its entire diesel machines [3].

Energy management is possible in EVs but not in diesel vehicles, and mining EVs can offer reliability, long life, precision and performance. Compared to the domestic EVs, autonomy in mining EVs is much simpler, which can reduce the overall operation costs. This can be accomplished through the predictability of the path and terrains around the mine site considering the capability of electric motors to respond to a given change in demand, which is one tenth of the time of diesel engines.

Table 2. Comparison of mining diesel vehicles versus EVs

Diesel Vehicles	Electric Vehicles
• Low efficiency (~35%) • Low overload capacity • High maintenance cost • Requires skilled mechanics for maintenance • Volatile diesel price • Transport and storage difficulties of fuel • Higher noise (~105 dB) and vibration • Can cause fog formation • High heat generation • Difficult to build autonomous • High component counts and low reliability • Difficult for data gathering and remote monitoring	• High elec. motor efficiency (>95%) • High overload capacity • Zero local emission (avoiding large and noisy ventilation system and resulting low ventilation, fuel, consumables, regulation checks and maintenance cost) • Low heat generation • Low kWh energy cost • Low maintenance • Lower noise (~85 dB) and vibration • Ideal platform for autonomous systems (including re-charging) • Modularised components and high reliability • Easy to obtain monitoring data
• Longer operating range • High specific fuel energy, ~13kW/kg • Lower capital cost (due to established mass production) • Fast and easy refuelling	• Limited operating range • Requires different fuelling (charging) infrastructure • Low specific "fuel" energy battery (~250W/kg) or fuel cell (1kWh/kg)/hydrogen (33kWh/kg) • Currently slow re-charging • Limited battery lifetime • Higher cost (but very likely to reduce by mass production and increased competition and new power electronics devices)

Although the history of cable-tied mining EVs goes 50 years back, the modern battery-operated mining machines are in development since 2015, and major electrically/battery powered mining machines are summarised in Table 3.

In one of the landmark applications, Canadian Goldcorp mining company's fully electric underground mine (near Chapleau in Ontario) uses an all-electric mobile equipment fleet (ranging from battery-powered underground vehicles, drilling and blasting equipment, to electric bolters and personnel carriers) offering high efficiency and improve health, safety and performance [4].

III. Features of Mining Microgrids and Examples

In general, microgrids can serve as autonomously working energy hubs to have access to different renewable energy sources and distribute it in the most efficient and cost-effective manner (Fig.1). The mine site deployment of an electricity microgrid with distributed energy resources and integrated battery energy storage can:

- offer relatively continuous power;
- provide power at higher levels of reliability,
- offer low variable cost and low maintenance cost;
- present higher capacity factor and hence reduces overall electricity cost;
- serve low power demands continuously and using sustainable renewable sources of power;
- reduce the system losses due to close proximity to the loads; and,
- has a positive impact on the power quality (specifically on voltage sag).

Table 3. Electrically/battery powered mining machinery

Machinery	Remarks and Companies
Electric rope shovels	• 1975 First cable-fed vehicle (USSR, France) • Used in surface mining and for loading in-pit crusher-conveyor systems and haul trucks • DC type available by Komatsu, Caterpillar and IZ-KARTEX, Liebherr, Hitachi
Electric Load-Haul-Dump (eLHD) trucks	• Commonly used underground vehicles. • High power density allowing better access. • By GE, Caterpillar (with fast on-board charging), Epiroc
Electric Haul Trucks	• Employed for ore transportation typically in difficult geological conditions, under stringent safety issues, and for large production • Komatsu using battery and hydrogen fuel cell technology (similar to Electric Nikola Badger Pickup Truck) • Sandvik Artisan: 50 ton payload, 3x more power than a diesel. • The emerging market includes a number of companies: Caterpillar, Volvo Group, John Deere, CNH Industrial, Komatsu and Epiroc. • ABB and CAT: trolley-based systems
Electric Drills	• An all-electric drill uses AC electric motor driving a hydraulic circuit which moves hydraulic percussive rotary hammers. • The drill can be transported from one location to another using an electric vehicle. • By Sandvik and IZ-KARTEX, Epiroc
Electric Service Vehicles	• Utility EVs used at an underground gold mine by Bortana-EV
Primary electric crashers	• By Volvo Construction Equipment in partnership with Skanska Sweden
Electric scoops, boomer and smaller trucks	• By Epiroc (Atlas Copco)
Electric locomotives	• Driver assist and unmanned types • Anglo American Platinum has launched a platinum-based fuel cell-powered locomotive
Battery-electric explosives charger	• By Normet
Rock bolting rig	• Electro-hydro
Battery-Powered LED Light Tower	• By Atlas Copco
Conveyors	• Multiple companies, • Distributed/central and usually induction motors

Note that modularity and mobility are two major characteristics of the microgrid technologies that enable expansion very quickly when needed and re-using technologies and facilities at a minimum cost.

Moreover microgrid systems require unique electronic controllers. Currently, some of the key players in microgrid controllers include Eaton, Schweitzer Engineering Laboratories, ABB, Honeywell, Power Analytics, Go Electric, S&C Electric, Siemens, Lockheed Martin, Homer Energy, GE Power, Emerson, Qinous, Advanced Microgrid Solutions, Princeton Power Systems and Emerson. The number of microgrid controller developers available in the market is indicative of the acceptance and future of the microgrid technology.

Additional comments about the benefits of mining electrification with renewable sources in a microgrid structure can also be made at this time:

- The common practice in underground mining is to ventilate the entire mine at all times. When the emission level is reduced by electrifying mining vehicles, ventilation on demand would be lower so that it can easily be accommodated using variable speed drives, which offers further energy savings.
- The cost of solar PV energy has been lower than diesel costs since around 2012 due to subsidies. However, “true grid parity” has also been reached (considering its intermittent nature and storage requirements) when we consider the absence of long transmission lines as well as the absence of power quality improvement devices at the point of common couplings.
- Low-cost renewable energy is likely to allow the integration of refining, processing and smelting industries, hence adding value and reducing shipping cost of raw ore material.
- Mine electrification is more than technology advancement. It has the potential to contribute to the sustainability of the microgrid industry and EVs in domestic applications as well as in remote towns. In addition, it can improve project economics and strengthen licencing to operate in Australia and overseas (specifically in island nations).

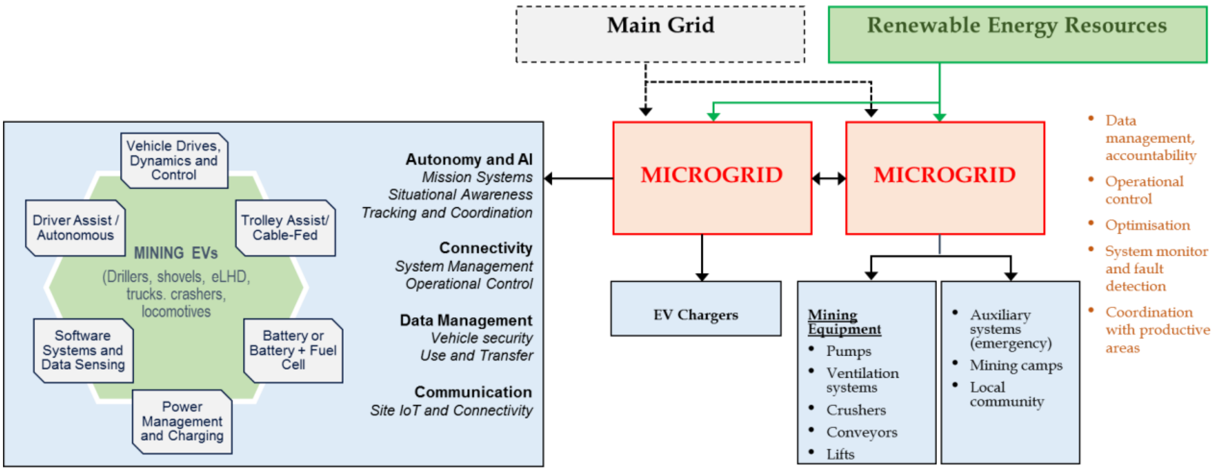

Figure 1. The basic components of mine site electric vehicles and their relationship with the broader mining microgrid.

- Serious health risk from diesel fumes and particulates in underground mines as well as centralised air conditioning prompts fears on the employees' health, possibly more in the light of future pandemics.

Although not all big mining companies share an agreed vision on the future of all-electric mining, there is agreement on the reliability of the energy, energy cost and safer and healthier work environment.

Significant developments have already occurred around the world on mining EVs and mining microgrids. Some selected mining microgrid examples and management systems are given below.

- The Australian Energy Storage Knowledge Bank (AESKB) (www.aeskb.com.au) flexible microgrid test system (270kW/270kWh) has been developed (See Fig. 2) which is available for deployment in any remote locations in Australia including mining sites [5,6].

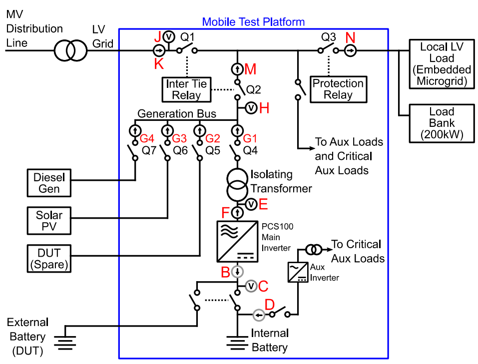

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Figure 2. The AESKB flexible microgrid test platform: a) The single line diagram of the system, b) The unit parked at the University of Adelaide with the diesel generator and local load.

- BHP Escondida Copper Mine (currently on gas) microgrid project in Chile to use 100% renewable energy. Note that Escondida's power requirements have risen due to an investment in a seawater desalination plant, and declining mineral grades. Note also that the mine site has access to excellent solar radiation and high winds.
- EDL's Coober Pedy microgrid project (a mix of wind, solar, batteries, flywheels, diesel and resistors, since 2017) offering the average share of renewables of about 70 %.
- Agnew gold mine microgrid in Western Australia: a hybrid system involving wind, solar, battery, gas turbines and back-up diesel.
- Rio Tinto aim to reduce the annual carbon footprint associated with Kennecott Utah copper mine by 65%, by purchasing renewable energy certificates and permanently shutting its coal power plant.
- 100% renewable energy in Chilean copper mining company Antofagasta by a mix of hydro, solar and wind.
- A solar power array with photovoltaic tracker (from Nomad solar PV tracker designed to be deployed in scalable 30kW segments) at Newmont's Akyem gold mine in Ghana.
- A solar-diesel hybrid microgrid for Zijin's Bisha copper and zinc mine in Eritrea.
- Hybrid solar-battery microgrid by Aggreko at Gold Fields' Granny Smith in WA.
- Pilbara iron ore mines with Alinta Energy built a solar power facility with battery storage connected to Alinta's Newman gas power station at Chichester, which includes the Christmas Creek and Cloudbreak mines. Aimed to provide 100% of Chichester's daytime stationary energy requirements and long-term cost reductions.
- Antofagasta's Centinela to achieve 100% renewable energy supply together with Engie Energía Chile, hence reducing energy costs significantly in stages from 2020 onwards and cancelling power purchase agreements by 2027.
- Galaxy Resources' Mt. Cattlin lithium mine in WA currently uses renewable energy sources for up to 15% of its total power, using solar PV tracking panels and has a plan to entirely power from solar and wind power, in the next three years, developed by Swan Energy.
- ABB Developed
  - Mining digitalisation through automated scheduling software, and,
  - Ability Operations Management System, to enable miners to get greater visibility and control of their mining operations delivering automation, electrification and instrumentation solutions for the Hydrogen Energy Supply Chain pilot project at Port of Hastings, Victoria.
- GE Mining, a division of GE Transportation, offers a broad range of mining equipment, propulsion systems and services as well as innovative solutions in mine electrification. GE's Advanced Energy Management Systems (AEMS) provides real-time data monitoring to better understand current and future energy usage and enable informed, proactive decisions about transmission of renewable energy. GE Mining also showcased its digital industrial solutions for the mining industry and introduced the Predix™-powered monitoring analysis and event management including collision detection.
- ComAp introduced Cloud Forecasting System for PV-Diesel hybrid microgrid applications.

IV. POTENTIAL ISSUES IN MINE ELECTRIFICATIONS

The analysis of a survey of miners and mining original equipment manufacturers commissioned by EY reveals that obtaining the full benefits of electrified mining require further skills and competencies for smart mining, involving numerous sectors and rethinking the fundamentals of mine design [7].

This paper also aims to define the key challenges in mine electrifications and to help articulate possible approaches towards acceptable solutions. The following challenges have been identified to initiate research discussions on potential issues on mine electrifications.

- The current mining EVs, listed in Table 3, can be considered as the pioneer of the future autonomous mining systems. They are likely to provide significant reference data from harsh mining environments to help the development of the future high-performance and networked vehicles with modularized spare units (for minimum maintenance, rugged, low-cost and high power density).
- Understanding electricity generated from braking when the mining vehicle is going along, swinging, rotating and dropping [see Fig. 3]; developing compact motors and other actuators to offer more responsive and manoeuvrable vehicles; adaptation to the varying conditions.

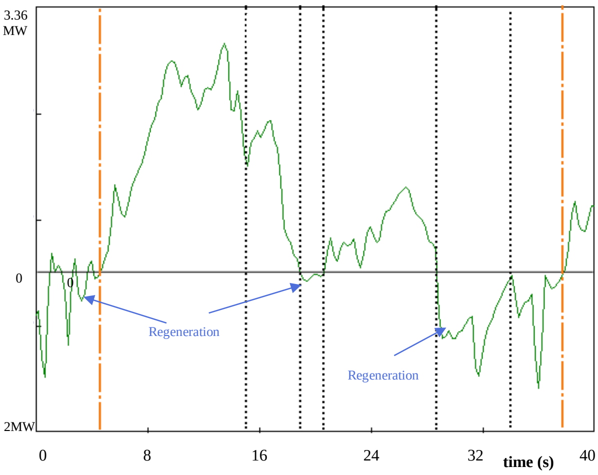

Figure 3. Active power flow during a shovel operation [8].

- Some critical mining EV technologies may include task-specific electric motors, traction/auxiliary battery systems and battery charging and/or swapping/replacement technologies, energy recovery and storage systems (such as super/ultracapacitors), and power electronics with extra features (such as on-board fast charging using wide band gap switching devices), vehicle to microgrid and even vehicle to vehicle power transfer.
- There is a number of mining vehicles among the most power-hungry systems. Their fast charging requires unique approach to consider battery type, high power charging resource development and on-board fast charging under harsh environments.
- Although logistical downtime can be very high in LHD vehicles (>35% in eLHD) which directly impacts mine efficiency, it can be avoided if the mining process is streamlined by communications, autonomy and control, which relies on fully electrified mines.
- Open pit distribution systems are complex systems having time varying topologies and highly dynamic load changes. Voltage regulation and power quality issues are recurrent in these types of power distribution systems. These problems have a high impact in the efficiency and reliability of the distribution system. We can study battery storage systems to offer solutions to these problems to develop a reliable and quality energy supply for modern open pit mines. Moreover, one of the main characteristics of mine´s electrical power distribution systems is the use of large power loads (high power motors in MW range) and static power converters. The operation of such loads generates power quality problems which require finding solutions to compensate reactive power. Furthermore, power demand control in mine´s power distribution systems can avoid power quality problems, specifically associated with operations of shovels and drillers [Fig. 4].

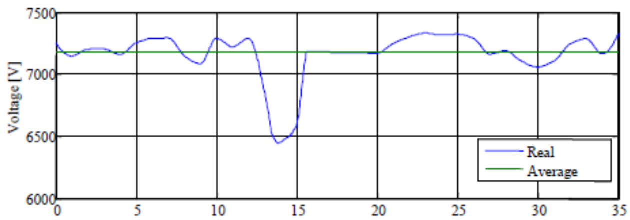

Figure 4. Voltage dip (rms!) during driller start [8].

- AESKB system can be utilised to investigate how to develop a multi-mode and transportable "mobile substation" for powering the components of mining microgrid as illustrated in Fig.1.
- Artificial intelligence (AI) can be used to improve operational efficiency, mine safety, and production workflow, which will involve coordinated mining-EVs with standardised communications. Note that electrified mining will become a highly controlled and data-rich environment, including the state of the energy utilisation, ventilation and pump data.
- Electric rope shovel is a major piece of equipment in coal mines consuming significant power. Hence, commissioning a new shovel in an existing power network requires a careful analysis of its impact on the network (including load flow, fault analysis, protection coordination, harmonic analysis and arc flash studies. A mobile microgrid (as in AESKB Microgrid) can eliminate the above concerns and require a local study in the light of a given mine site.
- The trend in mining electrification is to go off-grid since many mining sites are remote and national power networks are vulnerable to weather conditions and cybersecurity

attacks. However, these issues can be studied for a specific mine to improve reliability, control, monitoring and cyber security.

- Energy consumption modelling, operational and infrastructure adaptations and change in management structure can be studied. Proactive consumption methods can be explored and tools can be developed to enable the industry to manage energy consumption. Furthermore, data analytics tools can be developed to analyse electrical systems and to enhance their performance in different conditions.
- Investigation of other methods to accelerate the advancement and adoption of mining electrification technologies, including direct current microgrid solution for mines to improve reliability and efficiency [9].
- Mining microgrids' investigation can include:
  - exploring intelligent/autonomous controls to address system issues and faults, including automatic fault location, isolation and restoration (FLIRS) systems
  - charging mining EVs and their utilisation as backup power
  - mining town integration

V. Conclusions

Over the coming decades, mining operations will face increasing economic, environmental and social pressure to address the significant level of carbon emissions generated by the resources industry. The increasing availability of mine-specific or mine-adaptable electrification technologies, machinery, vehicles and infrastructure provide an opportunity for both resource companies and the support service industry to address these growing pressures and help transition to an electric mining future.

As it is highlighted in this paper, the transformation has already begun with several examples where electrification, mainly in the areas of mining EVs and microgrids, has been integrated in mining operations, across a range of commodities around the globe.

It is also clear that the adoption of IoT, automation and data-driven systems and technologies is critical in providing greater control and management of operations as well as deliver a safer working environment. Moving forward, several new research pathways can be seen for mine electrification that could have a further impact on mine operation safety, efficiency and, more broadly, lower carbon emissions.

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