FUTURE BATTERY INDUSTRIES CRC

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An overview of Australia's mining vehicle and mining equipment electrification

THE UNIVERSITY of ADELAIDE

FUTURE BATTERY INDUSTRIES MOBILE MINE REPORT

An overview of Australia's mining vehicle and equipment electrification.

A collaborative research project with University of Adelaide, University of Western Australia, Allkem, BHP, Energetics, IGO, Multicom, SA Department of Energy, Qld Department of Energy, and Mineral Research Institute of Western Australia (MRIWA).

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EXECUTIVE SUMMARY

A key driver for the strong interest in mine vehicle electrification is the net-zero greenhouse gas emission targets. While electric vehicles will generally have higher capital costs, the elimination of underground diesel emissions improves worker safety and reduces ventilation requirements, which can significantly shorten underground mine development and reduce operating costs. In addition, electric vehicles are expected to have reduced maintenance costs/improved reliability, and to form a pathway to future vehicle automation.

This report, prepared as a part of the FBICRC Mine Operational Vehicle Electrification (MOVE) project, provides insight into the current status of mine vehicle electrification in Australia. In preparing this report, the following has been included:

- a literature review including a discussion of available electric mine vehicles;
- the context of the motivation behind electrification to reduce greenhouse gas emissions;
- discussion of the main benefits of electrification, including a reduction in the operational costs and greenhouse gas emissions, improved health and safety of the workers in underground mines and potential improvement in site productivity;
- challenges and opportunities in mine vehicle electrification, and how the FBICRC MOVE project will help to mitigate some of the risks and challenges involved in mining electrification, and
- a summary of the industry perspective and aspirations.

Studies, surveys and recent trends in research and development (R&D) efforts suggest that the need for an energy transition in the mining industry is well recognised. However, the transition to mining electrification is complex and challenging. It will require investment in infrastructure, technologies and hardware, changes to processes and operations, and training and development of workers with new skills.

The MOVE Project has uncovered a significant gap in the knowledge of design, operation, and implementation of fleet electrification within the industry, including mining companies, OEMs and consultancies to achieve smooth electric fleet operation. Unlocking the full potential of electric fleets in the mining industry requires whole-of-system design and operational tools to advise the industry on the most technically and economically viable solution for electrification. The design tool must be able to determine the optimal battery size onboard the trucks, necessary charging infrastructure, backbone energy system, and an optimal scheduling system for regular charging of the trucks.

Another concern is the training and upskilling of the future workforce to work safely in electric mines. The development of a skilled workforce can be achieved in several ways, including by offering tailored training programs covering topics such as battery selection and specification, power electronics, safety, maintenance and operation of batteries, optimal system design and daily operation under renewable, battery storage and microgrid technologies.

While there are clearly challenges, the Australian mining industry is presented with a rare opportunity to fundamentally rethink and redesign the way mining operations are carried out and prepare the future workforce for the next evolution in mining.

This report intends to advise on the current status, gaps in knowledge, and challenges of mining mobile vehicles and equipment. As a result, the main power system and electricity generation required for electrification has not been discussed in this report.

1. MARKET NEED

1.1 Background

The way energy is consumed and produced for the mining industry in Australia has made it one of the major contributors to the effects of GHG emissions and climate change. Currently, most energy used in the mining industry comes from diesel combustion, and almost all mobile mine equipment is diesel-powered. The mining industry consumes about 14% of the total energy produced in Australia, with 51% from diesel, 19% from natural gas and 27% from grid electricity[1]. Accordingly, the mining industry is the second largest contributor to carbon emissions (102 Mt CO^2-e pa)[2]. What increases the concerns about the mining industry is that it has been the fastest-growing sector in GHG emissions for the past 30 years, as shown in Figure 1.

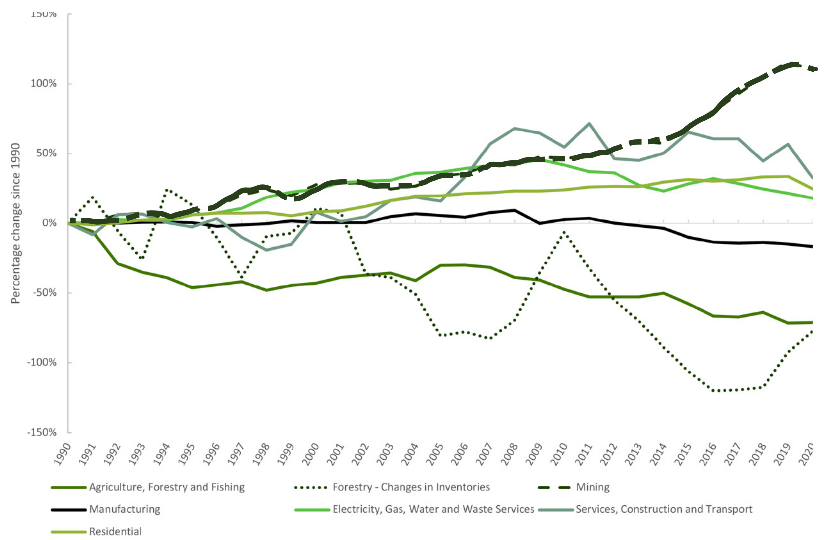


Figure 1. Australian emissions percentage change by economic sector from 1990 to 2020[2]

Aside from the environmental impact of using diesel fuels, there is clearly a worker health and safety imperative for electrification. Diesel particulate matter (DPM) and other emissions produced by diesel engines have been classified as "Group 1 - carcinogenic to humans" by the World Health Organization[3]. Also, the heat, noise, and fumes generated by diesel engines can create potentially dangerous conditions in the working environment, especially for underground mining operations. They thus can pose a serious threat to workers' health.

Among all potential solutions to decrease the health and environmental concerns of the mining industry, electrification is the most promising and necessary solution. Put simply, electrification means using electricity as the main energy source to power all mine operations, replacing fossil fuels such as diesel. For example, 11.2k Btu/ton of diesel fuel used at mine sites is for transportation, while 0.9k Btu/ton for drilling, 1.25k Btu/ton for digging, 2.5k Btu/ton for loading in wheel loaders, 1.8k Btu/ton for stacking and reclamation and 2.4k Btu/ton for other operational support activities[4].

Therefore, electrifying material extraction and movement, combined with using renewable power sources such as solar power, is a vital initial step towards achieving net-zero emissions operation. Battery electric equipment and vehicles (BEVs) have a strong potential to replace large diesel-powered vehicles in the mining industry. BEVs can reduce GHG emissions by avoiding diesel use and reducing the large electric power consumption required to produce the high ventilation air speeds needed to remove diesel exhaust fumes. They also provide a healthier working environment[5].

Australian Government emissions projections[6] to 2030, show that increasing automation and electrification of mining equipment can slow the increasing rate of direct emissions from the mining industry. The same report has also shown that producing more electricity from renewable energy sources is another key step in decreasing the mining industry's contribution to emissions by 2030.

Emissions are also released during fossil fuel extraction, processing, and transport. More specifically, fugitive emissions, as a substantial source of emissions from mining, are the unintentional release of gases such as methane and carbon dioxide associated with mining natural gas, oil and coal, which are not directly controllable. Australian fugitive GHG emissions from 1990 to 2030 are shown in Figure 2. The figure shows steady but slight growth in fugitive emissions from open-cut mines, while the underground coal mine values display a declining trend over the years. Unfortunately, these will not be affected by the electrification of mining vehicles and must be reduced by other means.

Stationary energy covers emissions from the combustion of fuels to generate steam, heat, or pressure, but not for electricity generation or transport[7]. Figure 3 shows Australia's stationary GHG emissions from 1990 to 2030. It shows the emissions from the mining sector (shown in black) had significant historical growth. It is expected to increase by about 10% from 2020 to 2030. This slower predicted growth in the future is likely due to improved diesel engines, greater electrification of mining equipment and increased automation[7].

Moreover, electric vehicles not only have zero tailpipe emissions when the battery is charged by renewable sources, but also have lower lifecycle GHG emissions[5], as shown in Figure 4.

Mining electrification also provides a pathway towards efficient, sustainable, safe underground and open-pit operations. New and adaptive technologies such as autonomous vehicles, digitalisation, communication networks and data analysis based on IoT technology can be integrated to reduce further operational costs during extraction, concentration, and transport. Also, the electrification of mine sites will improve outcomes related to social licence to operate, corporate social responsibility, and commitments to shareholders on emissions reductions. This will likely enhance company ratings on ethical financial funds. It is also expected to improve the ability of mining companies to engage local stakeholders and provide benefits to local communities, such as through sharing renewable power. However, transitioning to electrification in mining is complex.

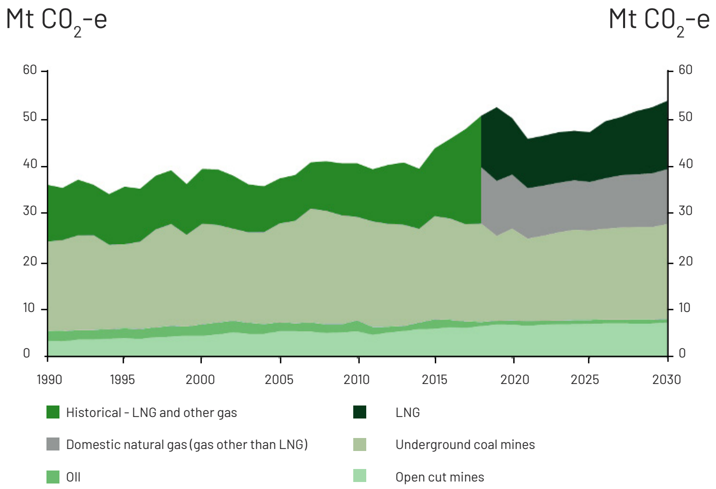


Figure 2: Australian fugitive emissions, 1990 – 2030 (projected)[6]

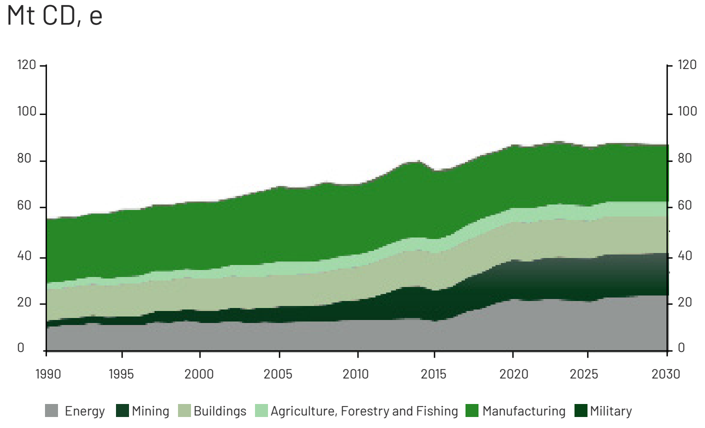


Figure 3: Australian stationary energy emissions, 1990 – 2030 (projected)[6]

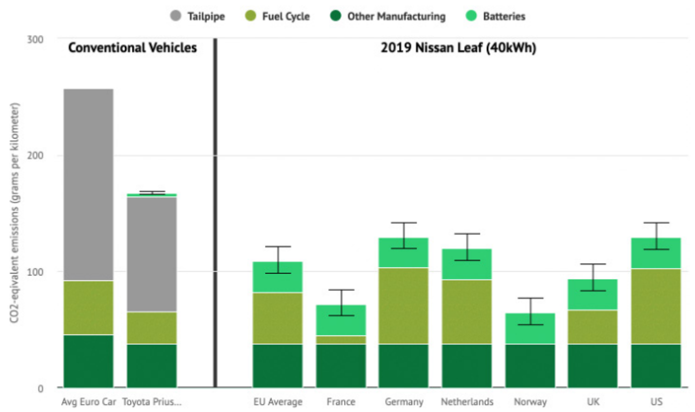


Figure 4: Lifecycle greenhouse gas emissions for conventional and electric vehicles[107]

It will require investment in infrastructure, technologies and hardware, changes to processes, and a workforce with new skills. A GMG report[8] states "it is clear that as an industry, there is a significant knowledge gap relating to electrification technologies and their capability." Therefore, a collaborative approach to research and development involving all stakeholders and research institutes is needed to fill the gaps and advance the technologies necessary for mining electrification.

This document outlines the current situation in Australian mining electrification of vehicles, the challenges and gaps in knowledge, the FBICRC-funded project, and future directions on material extraction and transportation.

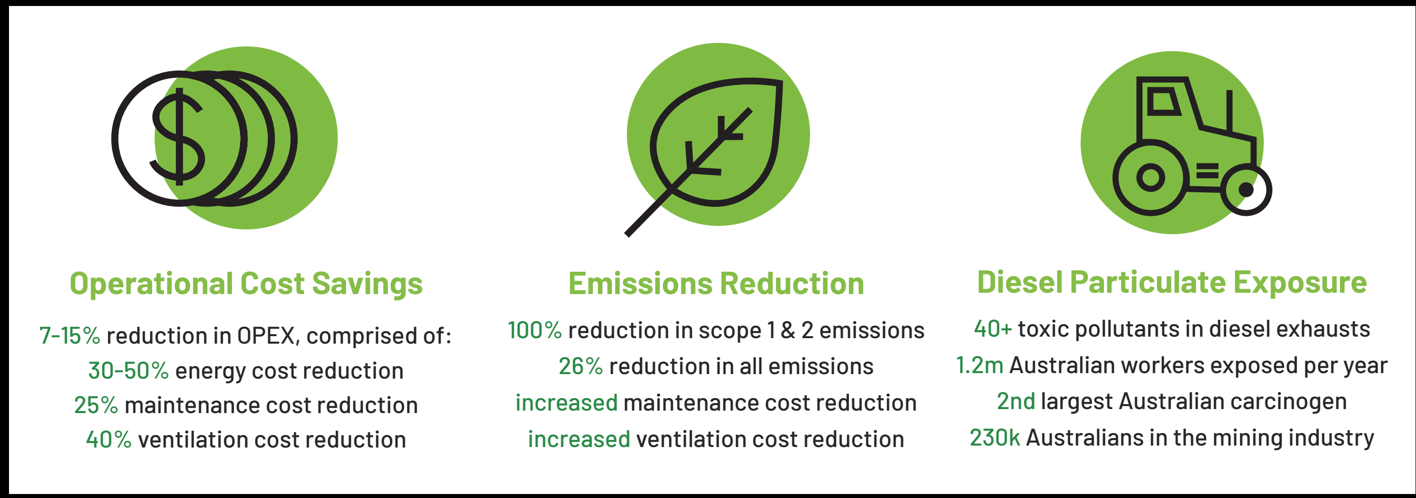
There are several drivers for mine vehicle and machinery electrification. Primarily this appears to be the reduction of GHG emissions and their effect on rising global temperatures, which is well recognised. While reducing GHG emissions is clearly the right thing to do, there are also long-term economic and worker health and safety benefits for mine vehicle electrification. Figure 5 summarises the projected benefits of mine electrification.

Firstly, manufacturers of products, especially eco-friendly ones like EVs, are keen to demonstrate sound ESG practices throughout the supply chain for their products. Before production is commenced, they may select materials with lower emissions. It is, therefore, not surprising that BHP and IGO (two partners in the MOVE Project) selected nickel mines for the FBI CRC case study, given the key nature of the material in creating batteries used in EVs and other applications.

Secondly, investors are increasingly diligent about the ESG practices of companies they invest in. For mining companies to continue attracting investors and maintaining their market value, they must demonstrate similarly sound environmental practices, which start with decarbonisation. Furthermore, new mine site operations are at greater risk of rejection by governments at the application stage if socially responsible, environmentally considerate plans are not included.

Finally, there are opportunities for mining companies to reduce their operating costs and improve safety and working conditions for mine workers, as discussed in more detail in sections 3.1 to 3.3 below.

Figure 5. Estimated potential benefits of mine electrification[8]



1.2 Improve mining economics

Mine electrification can help reduce capital and operating costs in several ways, as outlined below.

1.2.1 Reduction in operating energy costs

Energy costs comprise approximately 20% to 33% of mining operational costs. A fully electrified mine can expect a 30% to 50% energy cost reduction. An electrified mine would also be less sensitive to diesel price variability and possible government diesel incentive reductions[9]. Eliminating fuel transportation, required infrastructure, and onsite storage reduces energy costs. In addition, energy consumption in BEVs can be more effectively managed, offering opportunities to reduce energy consumption for the same amount of work. Regenerative braking is another mechanism to reduce energy consumption by recovering some of the energy used in the BEVs. Lee et al[10] indicate that the energy use and GHG emissions ratios of electric to diesel trucks range from 48 to 82% and 25 to 89%, respectively. In another study, Elangovan et al[11] showed that the diesel trucks in New York City's food distribution system consume 300% more energy than electric trucks and generate 40% more GHG emissions than electric trucks. It's worth noting that the energy efficiency of electric trucks can vary depending on a variety of factors, including the size and weight of the truck, the driving conditions, and the specific technology used in the truck. However, the general consensus is that electric trucks can be significantly more energy efficient than diesel trucks in many cases.

1.2.2 Reduction of operating maintenance costs

BEVs have considerably fewer moving parts than diesel vehicles, particularly in the case of ground-up designed BEVs, such as Tesla cars. This is expected to result in an approximate 25% reduction in maintenance costs. Electric trucks also provide greater opportunities for digitisation, monitoring and measurement, allowing engineers to predict electrical component failures and improve preventive maintenance, further reducing maintenance costs.

1.2.3 Reduction in capital and operating ventilation costs

A significant requirement for the ventilation of underground mines is to reduce diesel exhaust fume levels to acceptable values. Electrifying mines eliminates diesel exhaust gases and the accompanying waste engine heat and are estimated to produce a 40% reduction in ventilation costs. In general, the ventilation power is proportional to the cube of the air speed. Thus, even small reductions in the required ventilation air speed can result in substantial power savings.
Note that this will not apply to coal mines where flammable gas leakage considerations primarily drive ventilation requirements.

In addition to operating costs, an electric haul system enables the design of a cheaper and quicker-to-build ventilation system. As a result, electrification will reduce the CAPEX during mine establishment and allow quicker access to the ore body, bringing significant revenue improvements. For this reason, in some cases, the biggest financial benefits of electrification may be realised during the mine design and construction.

1.2.4 Reduction in total operational expenditure (OPEX)

The above described reductions in energy, maintenance and ventilation costs are estimated to result in an operational expenditure reduction of 7% to 15%[8,12]. This is significant and may likely create new opportunities to mine previously uneconomic ore bodies.

1.2.5 Pathways to mining vehicle optimisation and automation

The electrification of mine vehicles and machinery will result in more real-time information about the vehicles and how they are used. This provides an opportunity to optimise the use of these vehicles to reduce costs. For instance, information about the battery's state of charge, temperature and state of health could help design better charging, discharging and maintenance routines to avoid excessive battery degradation.

The electrification of mining vehicles also provides a pathway towards future automation. This will provide further opportunities to reduce costs and improve the safety of mining.

1.2.6 Improvements in lower grade ore extraction economics

Improvements in hauling electrification, digitalisation, automation, and the use of renewable energy, combined with advancements in processing technologies, are enabling the economically viable extraction of lower grade deposits. Automated trucks and drills that run continuously with fewer breaks due to electrification and automation contribute to increased productivity and less downtime. Also, sorting, sensing, and AI technologies help identify and separate ore from waste, reducing the amount of material that needs processing. Since extracting metals from lower grade ore consumes more energy per unit of metal produced, the use of renewable energy, such as solar and wind power, can decrease energy costs and increase economic viability. Moreover, lower-grade deposits often offer larger mineral resources and longer mine lives, making them more attractive to investors seeking stable revenue streams over an extended period. Sustainable mining practices are crucial for responsibly extracting minerals to support the renewable supply chain. Advancements in technology and improvements in mining practices foster more efficient and sustainable extraction, which helps ensure a steady supply of critical minerals for the global economy.

1.3 Need to reduce GHG emissions from mining

According to a 2021 EY report[13], global mining executives ranked environment, social and governance (ESG), decarbonisation and license to operate as the top three risks and opportunities facing their business over the next 12 months. Also, recent research[14] shows that the successful implementation of ESG and sustainability initiatives make mining companies more attractive to investors and financiers. Additionally, building climate-resilient mining and metals businesses have been identified as a trend[15] for redefining mining and metals organisations, where the industry must have one eye on carbon taxes. In the following subsections, we explain the ESG-related motivations behind electrification in more detail.

1.3.1 Greenhouse gas (GHG) emission targets

There is increasing pressure on nations to comply with global GHG emission targets and be seen as socially responsible. This will increase the scrutiny of all contributors to GHG emissions. As a critical industry in Australia with a considerable share in total GHG emissions, the mining industry will face increased scrutiny to reduce its emissions. It is estimated that mine electrification combined with renewable energy integration could result in a 100% reduction in Scope 1 and 2 emissions and an up to 26% reduction in all emissions[8].

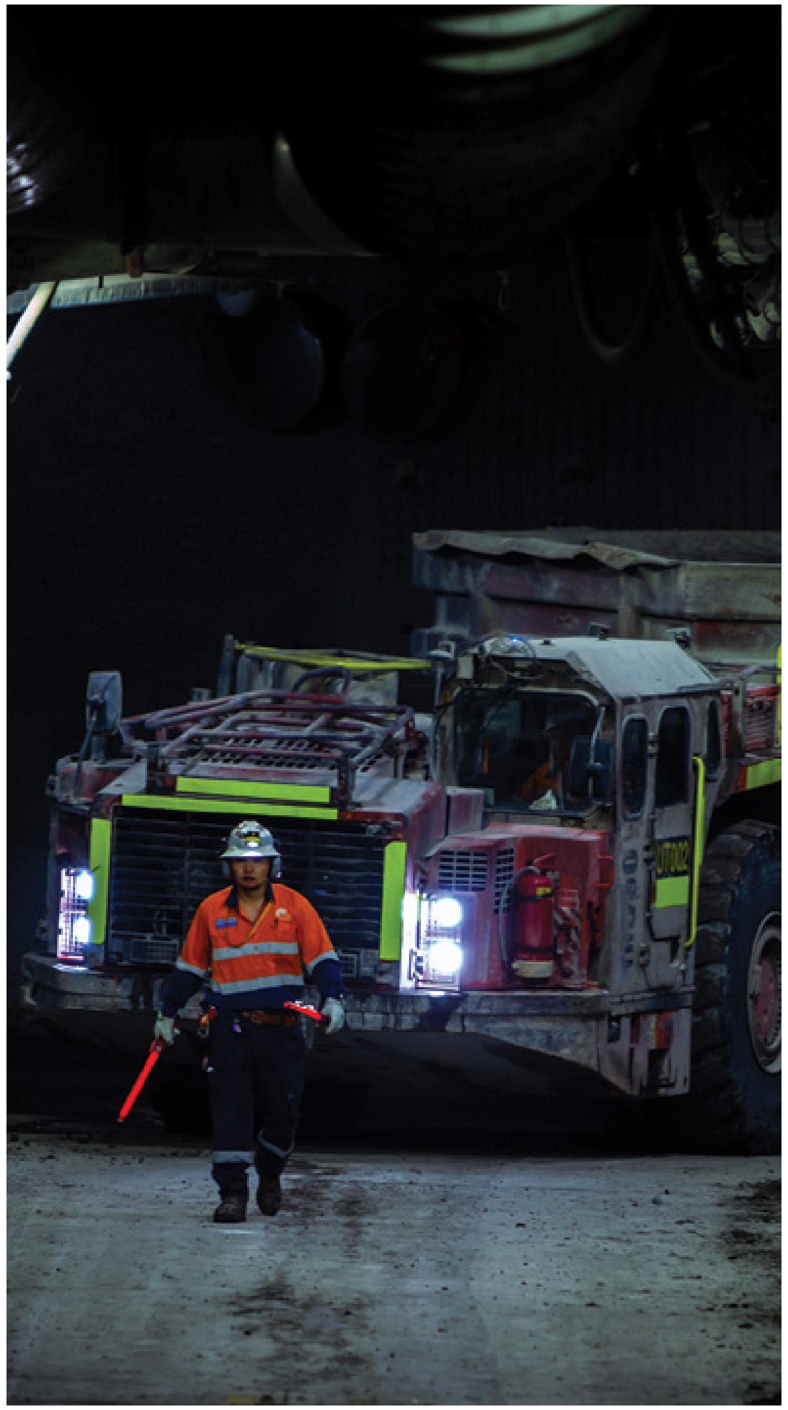
1.3.2 Stakeholder interests

Social influence is becoming increasingly important for driving global changes. End users such as EV manufacturers are prioritising showcasing the "greenness" of the manufacturing of their products, given this is important for some of their likely target markets. This mainly affects metals used in batteries, such as lithium, nickel, cobalt etc., but also other common metals in vehicles, such as iron, copper etc.

"Socially responsible" investing has been around for many years but has become significantly more popular recently. There is an increasing influence from superannuation funds which are seeing growing demand from their members for ethical investing. It has been estimated that ethical investing may represent about 25% of all managed funds and thus is an important economic driver[8]. Example outcomes of ethical investing have been difficulties for some coal mining companies to raise capital and some investment funds indicating that they will not invest in carbon-emitting companies in the future[8].

1.3.3 Society

A mining company's credentials in good environmental stewardship assist in the social licence to operate within the community. One of the negative impacts of mining on the local communities is air pollution and micro-climate change. Mine electrification could mitigate this negative impact fully or partially. In addition, the industry can provide clean and green energy to local communities and nearby townships at a lower cost than existing fossil-fuel generators at a perhaps higher reliability.



1.4 Improving mining worker safety

BEVs can substantially improve mining worker safety and health in underground mines by avoiding emissions, noise, and heat from diesel engines.

Diesel emissions include carbon monoxide and dioxide, nitrogen and sulphur oxides, hydrocarbons and particulates. These have significant health concerns for workers, and strict standards require substantial capital and operating expenses to implement appropriate ventilation to reduce the concentration of emissions in the air[9], which can account for up to 40% of the total energy usage on a mine site[16]. It has been estimated that up to 1.2M Australian industry workers per year are exposed to potentially dangerous levels of diesel particulates[8]. With the electrification of trucks and machinery in a mine site, these emissions will be eliminated entirely, improving workers' and nearby communities' health and well-being.

While EVs eliminate health concerns, they introduce new safety issues, including battery operation and charging/swapping challenges. Due to the limited storage capacity of batteries, they will need to be charged/swapped regularly. It is expected that high charging power and large energy storage capacity of the batteries are required; thus, careful processes need to be implemented to ensure worker safety. In addition, battery swapping may bring safety concerns associated with removing and exchanging large, heavy battery units. Batteries also require comprehensive battery management systems to monitor each cell, ensuring correct operation and shutting down the battery in the case of a fault. There is also a small but not insignificant risk of battery fires. Therefore, appropriate modelling and safety procedures are needed in these situations.

The Australasian Fire and Emergency Service Authorities Council (AFAC) is the national council for fire, emergency services, and land management in Australia and New Zealand, and has released a report in 2023 regarding incidents involving electric vehicles[17] which outlines a variety of hazards related to battery operation as follows.

- Thermal runaway is an uncontrolled chain of exothermic chemical reactions in a cell that results in rapid temperature rises and the generation of flammable and toxic vapours, which can lead to exterior temperatures above 1000°C.
- The dangers of high voltage (HV) are the risk of electrocution from direct connection to the HV battery, the possibility of lethal levels of DC electricity in damaged HV batteries, and the presence of AC when EVs are on charge.
- The intensity of a fire in an EV is directly linked to the state of charge (SOC) of its battery or cell, with a vehicle battery at SOC between 50-100% or freshly charged is more likely to behave violently in a fire than one with an SOC below 30%, and EVs are more vulnerable to fire events while connected to or recently disconnected from a charger. Thus, in investigations it is important to identify whether the EV was connected to a charger at the time of the incident.
- An EV can move unexpectedly due to lack of immobilisation or stabilisation, without making any sound. So immediate application of wheel chocks is essential to prevent unforeseen vehicle movement.

The NSW Resources Regulator has outlined a list of safety recommendations that mine operators should implement in the case of a lithium-ion battery fire, as follows:

- Emergency management plans must include suitable controls and procedures for lithium-based battery fires[18].
- First responders have ready access to, and are trained in the use of, PPE suitable to protect from exposure to toxic and corrosive chemicals that may be liberated during and following a thermal runaway event.
- First responders are trained in the mine's procedures and understand the risks associated with the lithium-based batteries in use at the mine. This should also include awareness of the risk of electric shock and burns from stranded energy in a damaged battery unit and of exposure to toxic gases.
- Ventilation quantities in areas where battery powered equipment is operated, stored or charged is sufficient to dilute any potential accumulation of flammable gasses in the event of a battery failure. In the case of an underground charging station, this should include ventilation direct to a return airway.

Emergency procedures require a damaged battery unit to be removed from the underground workings and stored away from personnel, buildings or other vehicles, and is monitored until correctly disposed.

2. INDUSTRY PERSPECTIVE, ASPIRATIONS AND REQUIREMENTS

2.1 Industry perspective

Mining companies tend to avoid taking risks that affect safety and productivity. Finding profitable ore bodies already involves significant risks, and there is a preference to minimise further risks. There is increasing importance on emissions reductions from buyers of mineral products (mainly for electric transportation applications) and investors.

The mining industry widely acknowledges the imminent shift to electrification and the need for broad collaboration within the industry to achieve this goal. This is evidenced by recent industry initiatives that are presented in Section 4.1.2. According to the 2020 survey by State of Play report[8] from industry executives:

- 57% expect the energy transition to be the global trend that will significantly impact the industry over the next 15 years;
- 89% expect mine sites will electrify within the next 20 years;
- 61% expect the next generation of mines will be all electric;
- 83% expect renewable energy technologies will significantly change mining operations over the next 15 years; and
- 98% view mine automation as the technology that will benefit the most from electrification.

2.2 Industry aspirations and requirements

2.2.1 Public commitments

Many mining companies have made public commitments towards GHG emission targets. For instance, BHP is actively seeking to reduce its GHG emissions, and has indicated it is on track to meet the following targets:

- Ensure FY2022 emissions are less than or equal to FY2017 levels[19];
- Ensure FY2030 emissions are at least 30% lower than FY2020 levels[19].
- In FY2020, BHP committed to spending at least US$400M in GHG emission reduction technologies over the next five years[19]. It also seeks to reduce the number of workers potentially exposed to significant levels of diesel particulates, respirable silica and coal mine dust. This has declined from over 4,000 workers in 2017 to about 1,300 in 2021[19].
- While BHP does not directly make a mining EV commitment, it is actively involved in two vehicle electrification projects (Charge On Innovation and Komatsu GHG Alliance)[19]. The BHP targets described above are expected to be representative of the majority of other Australian mining companies.

In summary, mining companies are taking action to decrease their greenhouse gas emissions, and mine vehicle electrification is a key technology in implementing this. Given the considerable uncertainties in mine electric vehicle availability and costs, companies are reluctant to set a public timeline and commitment. However, our discussions with the industry partners have strongly suggested that it is not a question of if but when mine vehicles will be electrified.

Larger mining companies generally have the internal capability for research and development and greater resources, and so tend to be "first movers" with new technologies and processes. On the other hand, mid-sized and small mining companies tend to be "fast followers" once the technologies are more reliable, road-tested, affortable and come with OEM warranty. Thus often technology development is driven by appetite and ability to shoulder the risk.

3. CONTEXT OF MINING VEHICLE ELECTRIFICATION OPPORTUNITY

3.1 Mining in Australia

Mining is a key component of the Australian economy. In 2019-20, it contributed roughly 10% of the Australian gross domestic product, resulting in resource and energy exports of about A$220B, and employed about 260,000 people[20].

Australia's mining exports have continued to grow in both quantity and value. Australia is now the world's largest exporter of iron ore, more than half of all iron ore exports, with a value of about A$94B in 2020-21[20]. Australia is also a major producer of bauxite, gold, manganese, zinc, cobalt, copper, nickel, lithium and uranium[21,22]. Therefore, it is crucial to take the necessary steps towards net-zero mining, ensuring the industry stays competitive globally regarding cost, scope 1 and 2 emissions, and ESG factors.

3.2 Current Australian mining operational processes

3.2.1 Energy usage in mining

Energy costs can account for 20%-33% of mining operating costs[16]; thus, it is important to manage these effectively.

The mining sector represents about 10% of Australia's total energy use, which has increased by about 6% per year over the past decade due to growth in the sector[23]. In the 2019-2020 financial year, the Australian Bureau of Statistics reported that the mining industry consumed about 34,300 GWh of electricity (coal 63.1%, natural gas 26.8%, renewable energy sources 8.6% and other sources 1.5%)[1]. It is expected that the contribution of renewables will increase over time as mining companies are making significant efforts to implement renewable energy sources, such as solar and wind power, to reduce their carbon footprint. A breakdown of Australian mining energy usage has been described below by highlighting the changes of different sources of energy consumption over decades:

- 1900s – 1940s: In the early years of mining in Australia, coal and wood were the primary sources of energy. In 1900, the mining industry in Australia consumed 1.7 million tonnes of coal and 0.7 million tonnes of wood. By 1940, coal consumption had increased to 4.4 million tonnes, while wood consumption had declined to 0.1 million tonnes[24].
- 1960s – 1970s: Diesel engines and electricity became more widely used in the mining industry. In 1975, the mining industry consumed 177 million litres of diesel and 1,600 gigawatt-hours of electricity[24].
- 1980s – 1990s: Oil and gas became important sources of energy for the mining industry, particularly in remote areas. In 1990, the mining industry consumed 1.3 million tonnes of oil and 0.6 billion cubic metres of gas. Renewable energy sources such as solar and wind power were also starting to gain traction. By 1997, there were 18 wind turbines and 14 solar systems installed at mining sites across Australia[25].
- 2019 – 2020: In recent years, natural gas has become a popular source of energy in the mining industry, particularly in Western Australia. In 2019-20, the mining industry in Western Australia consumed 4.4 billion cubic metres of natural gas. Solar and wind power have also gained momentum in recent years. In 2020, the Australian mining industry installed 52 MW of new solar capacity and 18 MW of new wind capacity. It's worth noting that coal still remains a significant source of energy for the mining industry in Australia. In 2019-20, the mining industry consumed 3.6 million tonnes of coal for energy purposes. The breakdown in percentage is shown in Figure 6[25].

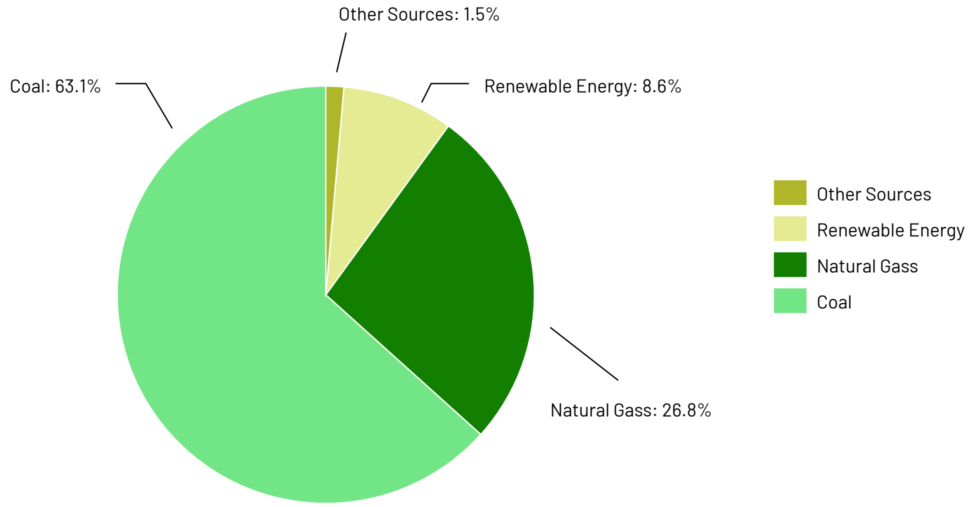


Figure 6: Breakdown of Australian mining energy usage in 2019-2020

The mining energy intensity, or the energy required per tonne of product, can vary significantly across different types of mining. Figure 7 shows the estimated on-site energy intensity for coal, minerals and metals based on data from the United States[23], along with a breakdown of the major energy usages for each type of mining. The data includes both the mining and the on-site beneficiation. The data shows that diesel usage, including vehicles and machinery, accounts for at least 33% of the total energy usage for all three mining types. Note that comminution, the process of breaking up mineral ores into smaller fragments using crushers/grinders, also consumes significant energy.

Ventilation is essential in underground mines to remove diesel exhaust fumes. A higher level of ventilation is required in coal mining to minimise the risk of explosions caused by the natural leakage of flammable gases (e.g., methane). These leaks, known as fugitive emissions, are a significant source of GHG emissions. Minerals have much lower energy intensity (energy per unit of production) than coal or metals because of the limited requirements for ore processing.

Figure 8 shows that metals have a wide range of on-site energy intensities with about 150-200 kWh/tonne for gold, about 80 kWh/tonne for copper, about 40 kWh/tonne for iron ore and about 13 kWh/tonne for bauxite. These differences are mainly due to the onsite processes concentrating the ore and removing waste material (beneficiation). Iron ore and bauxite require minimal onsite beneficiation, so energy consumption primarily comes from diesel for transportation and extraction. On the other hand, copper and gold require substantially higher onsite beneficiation, and most energy usage is electricity[23]. Therefore, to reduce GHG emissions, it is important to electrify the existing fossil fuel-operated vehicles and machinery and processes while deploying more renewable energy instead of fossil fuel generation units to feed the electrical loads.

It is expected that the mining energy intensity will rise as the average concentration of ores decreases and overburden increases, as the ore concentration has roughly halved and the average amount of overburden has roughly doubled over the past 30 years. This trend is expected to continue in the future[23].

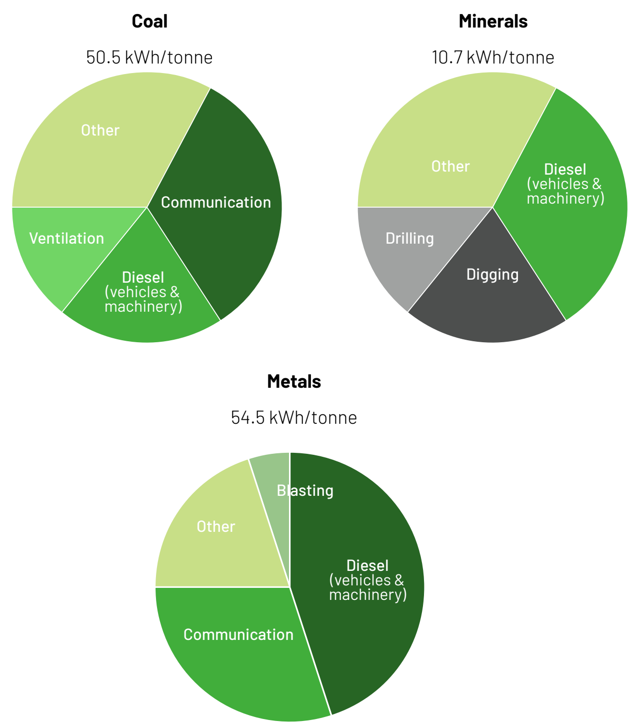


Figure 7. Estimated mining energy intensity during mining ore, transportation and on-site beneficiation, and breakdown for coal, minerals and metals based on US data[23]

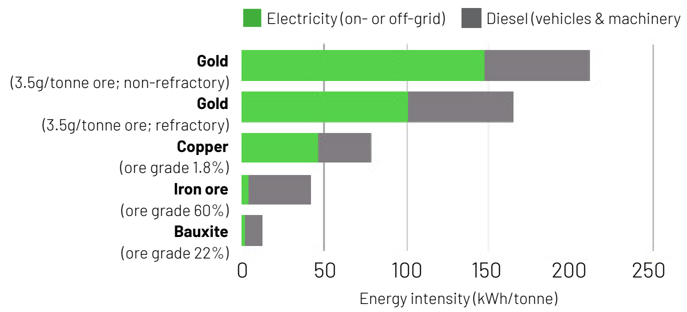


Figure 8. Estimated ore mining and on-site beneficiation energy intensity for different metals based on US data[23]

3.2.2 Cost of energy supply for mining in Australia

Figure 9 shows the significant variation in diesel prices between 2012 and 2021, and Figure 10 shows the total spending of diesel fuel for mining industries in the last few years. It can be seen that the total spending on diesel fuel has dropped significantly. Partially it is due to the increase of the usage of renewable power in the mining industries at recent years. Note that the Australian Government provides diesel fuel tax credits (also known as fuel tax rebates) to eligible businesses, including mining companies, that use diesel fuel for eligible activities. These credits are intended to offset the excise or customs duty paid on diesel fuel. The current rate of the diesel fuel tax credit is AUD 0.427 per litre for fuel used in off-road activities, such as mining, and AUD 0.164 per litre for fuel used in light vehicles and other non-business activities[26]. Figure 11 shows the price of natural gas that has recently risen substantially in major cities in Australia. Given the high energy usage of mining, primary energy price fluctuations can significantly affect the economics of mining.

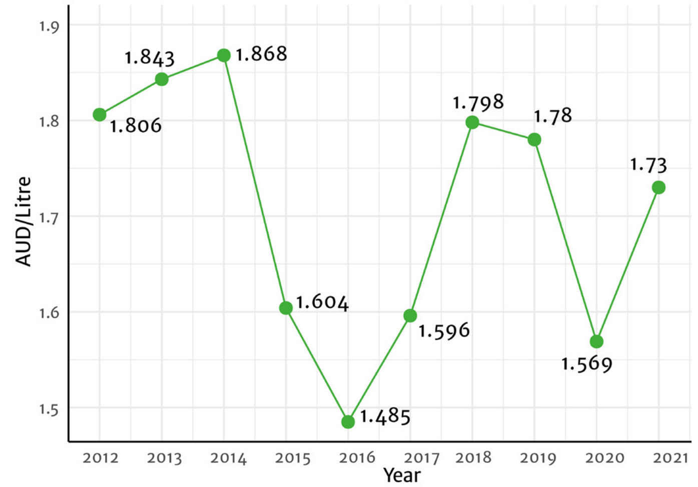


Figure 9: Historical Australian average diesel price for mining sites including GST and excise[27]

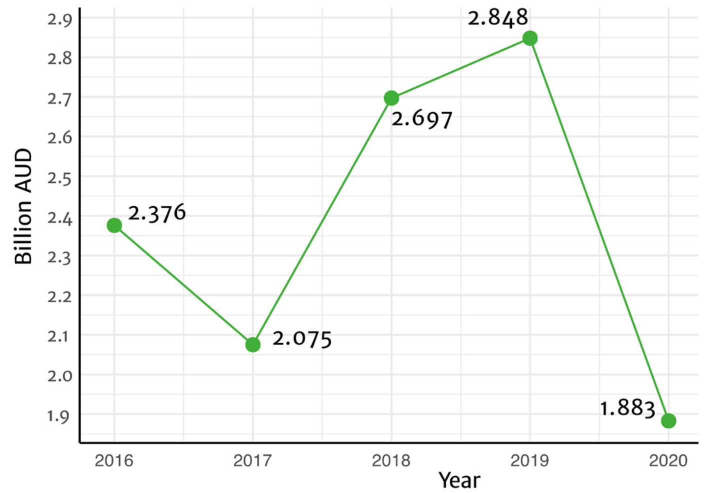


Figure 10: Total spending on diesel fuel for mining industries in Australia[28]

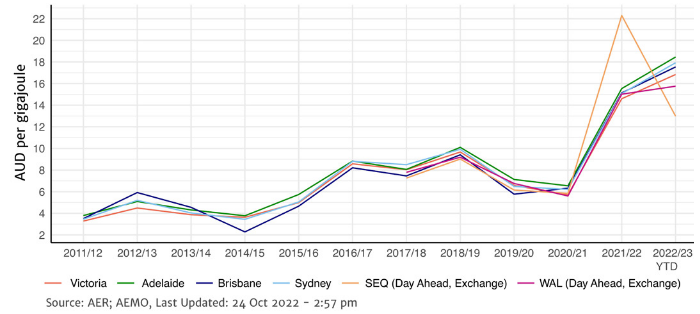


Figure 11: Gas market price variations from 2011 to 2022 in major cities of Australia[29]

Diesel is usually transported by road or train and involves significant logistics to move large fuel volumes to remote mining destinations. Large onsite storage tanks are also necessary to improve the security of supply. Turning to renewable energy will reduce the dependency on fossil fuels, lowering or eliminating the cost of fuel transportation and onsite storage. At the same time, Australian mining electricity prices range from less than \$0.10/kWh for grid-sourced electricity, \$0.15 to \$0.35/kWh for off-grid diesel power, and \$0.10 to \$0.30/kWh for electricity produced from gas pipelines[23].

Mining companies that require off-grid electricity often have contracts with Independent Power Producers (IPPs) for a period of 5 to 10 years to supply their electricity. These contracts generally have fixed and usage-based charges, with the mining companies covering fuel expenses, which typically account for over 80% of the total electricity cost[23]. A fuel efficiency incentive mechanism is usually in place to encourage efficient energy generation.

3.3 Proposed electrification approach

The overarching goal of the MOVE project is to develop general-purpose, flexible software tools to assist mining sites in transitioning to battery-electric vehicles. These tools will help with the following:

- Vehicle onboard battery sizing and optimal scheduling
    - Design of the optimal charging infrastructure for vehicles
    - Scheduling and operation
- Power system design
    - Energy sources: grid, renewable energy, diesel etc
    - Energy storage: batteries etc
    - Operation: interactions with the grid, local communities, vehicles etc
- Development of education packages that will allow the training of technical staff suitably prepared for the new battery-electric mines of the future

Due to the low battery energy density, electric haul trucks need a large battery pack to operate, leading to higher costs and lower productivity from the added weight and volume of the battery pack. Therefore a well thought out charging infrastructure is necessary to operate the fleet seamlessly with a sufficient but manageable battery capacity.

3.3.1 Electrified haul truck charging technologies

Different technologies can be considered through a comprehensive techno-economic assessment to meet the charging requirements for electric haul trucks in underground or open-cut mines. These existing charging technologies are briefly introduced below.

Fast charging: Fast charging stations can recharge an EV's battery in less than half an hour. They provide excellent energy efficiency (>90%) with a high charging rate (>150kW) for an EV. From the power system's viewpoint, they also provide electricity with a high-power factor (>0.95) and low total harmonic distortion (typically THD<5%). However, the high charging power can adversely affect the electric power system and battery lifetime, generating higher power losses due to higher currents drawn from the existing network causing increased resistive (I^2R) losses in the transmission lines, transformers and generators.

Table 1 and Table 2 show some specifications of two 350kW DC fast chargers for domestic EVs, the PK350 charger, manufactured by Tritium, and the Terra High Power Gen III charger, by ABB. The installation cost estimate for the fast-charger units depends on different factors such as the power level, installation site characteristics, and the charger's required equipment. The price of a 350 kW charger is estimated[30] to be between USD128,000 to 150,000.

TABLE 1: TECHNICAL SPECIFICATIONS OF THE TRITIUM PK350 CHARGER[31]

CHARGER POST	
EV Connectors	CCS type 2 CHAdeMO
Output Power	Up to 350 kW DC
DC Output Current	Up to 500 A CCS (liquid cooled) Up to 200 A CHAdeMO
DC Output Voltage	Up to 920 V DC
Efficiency	≥ 98.5%
Operating Temperature	-35°C to 50°C
Dimensions (H × W × D)	2000 × 980 × 525 mm
Weight	320 kg
POWER UNIT	
Power Factor	≥ 0.99
Efficiency	≥ 0.98
Dimensions (H × W × D)	2310 × 610 × 1060 mm
Weight	593 kg
THD	≤ 5%

TABLE 2: TECHNICAL SPECIFICATIONS OF THE ABB TERRA HP GEN 3 CHARGER[32]

CHARGER POST	
EV Connectors	CCS type 1 CCS type 2 CHAdeMO
Output Power	Up to 350 kW DC
DC Output Current	Up to 500 A CCS (liquid cooled) Up to 200 A CHAdeMO
DC Output Voltage	150-920 V DC
Efficiency	≥ 94%
Operating Temperature	-35°C to 55°C
Dimensions (H × W × D)	2458 × 590 × 425 mm
Weight	250 kg
POWER UNIT	
Power Factor	≥ 0.97
Efficiency	≥ 0.94
Dimensions (H × W × D)	2030 × 1170 × 770 mm
Weight	1340 kg
THD	≤ 8%

Battery swapping: This involves replacing a depleted EV's battery with a fully charged one, typically in about 3 to 5 minutes. It significantly improves vehicle availability compared to fast chargers[33]. This reduces queuing time and allows for slow charging of spare batteries, reducing battery degradation and losses and avoiding the need for high current during charging. Compared to fast chargers, battery swapping stations may have higher upfront costs due to the higher number of battery packs required and capital infrastructure cost, but lower battery replacement costs due to slower charging. Another disadvantage of battery swapping stations is that they need a fixed-mounted infrastructure that may not be easily relocated. The final cost comparison will depend on factors such as the number of trucks, usage patterns and local market conditions.

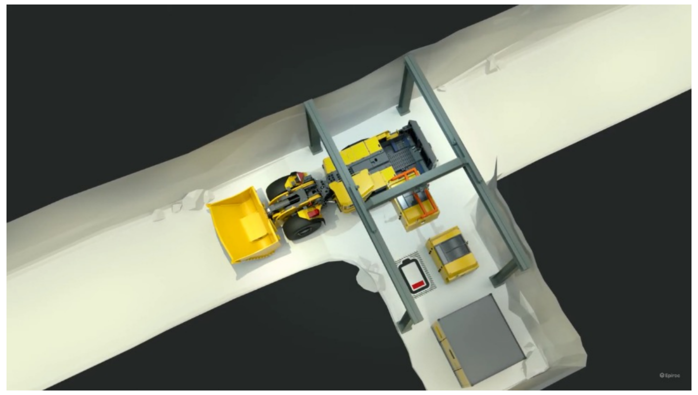


Figure 12: Example of battery-swapping equipment

Companies like Tritium, CATL, Epiroc, and Sandvik are developing battery-swapping technology for heavy-duty electric trucks. Figure 12 shows a conceptual design by Epiroc for a battery-swapping station in an underground mine. The cost of deploying battery-swapping technology in an underground mine is uncertain due to the technology's immaturity. Chen et al[34] estimated the total construction cost of one battery swapping station for domestic vehicles at USD 500,000.

Trolley assist system: The trolley assist system supplies the EV drivetrain through an overhead cable while the vehicle is in motion, over part or all of its operating cycle. This is similar to electric trains or trams. This allows for smaller batteries and increased productivity. In addition, as one of the most significant advantages, trolley assist charging potentially enables trucks to travel at a higher speed uphill (e.g., increasing uphill speed up to 80% and reducing cycle times up to 20%[35]), which improves the productivity. However, this charging technology offers limited operational flexibility and needs fixed infrastructure. Moreover, high infrastructure costs, safety, and configuration issues are among the disadvantages of trolley-assist systems.

Trolley assist technology is mature, and a number of mine sites are using this technology worldwide. It is presently more commonly used for surface mining operations, where truck sizes are larger and space is less constrained. For example, the first generation of trolley assist system used a 3 MW traction substation which provided 1200 Vdc for the trolley-assist feeder. Given the demand for bigger trucks, more recent systems use up to 10 MW traction substations and a nominal dc feeder voltage of 2600 Vdc.

The cost of erecting a trolley assist system varies from site to site. However, as a rough estimation, the total installation cost (including catenary overhead lines and pylons, substation, connection to the grid, transformer and rectifiers) is estimated to be 2-3 million Euros per km. Figure 13 shows ABB's conceptual design for trolley-assist charging infrastructure in the Copper Mountain mine, Canada.

Figure 13: ABB trolley assist system for Copper Mountain in Canada

Wireless charging: Wireless charging technologies enable electric vehicles to be charged while moving over an air gap of about 250 mm without wires[36]. This new type of charging technology can reach about 90% efficiency and may have lower operational costs than fast charging and battery-swapping stations. However, the rough conditions in an underground or open-cut mine could greatly increase the cost of deploying this solution. Also, considering the size of the onboard batteries and drivetrain, the required charging power could be an order of magnitude higher than what commercial wireless chargers are currently capable of delivering.

The wireless charging system is in its early stages of market development. SAE J2954, a standard developed by SAE International for unidirectional wireless power transfer for light-duty electric vehicles36, defines three charging power levels with maximum powers of 3.7 kW, 7 kW, and 11 kW. Another standard, SAE J2954/2, has been developed for charging heavy-duty electric vehicles at a maximum power of 500 kW[37]. In a field trial[38] under the UNPLUGGED project, 3 kW and 50 kW wireless charging systems were tested in urban locations. Another study by IPT PRIMOVE evaluated the feasibility of dynamic wireless charging at various locations in Germany and Belgium using different vehicles and charging capacities up to 180 kW[39].

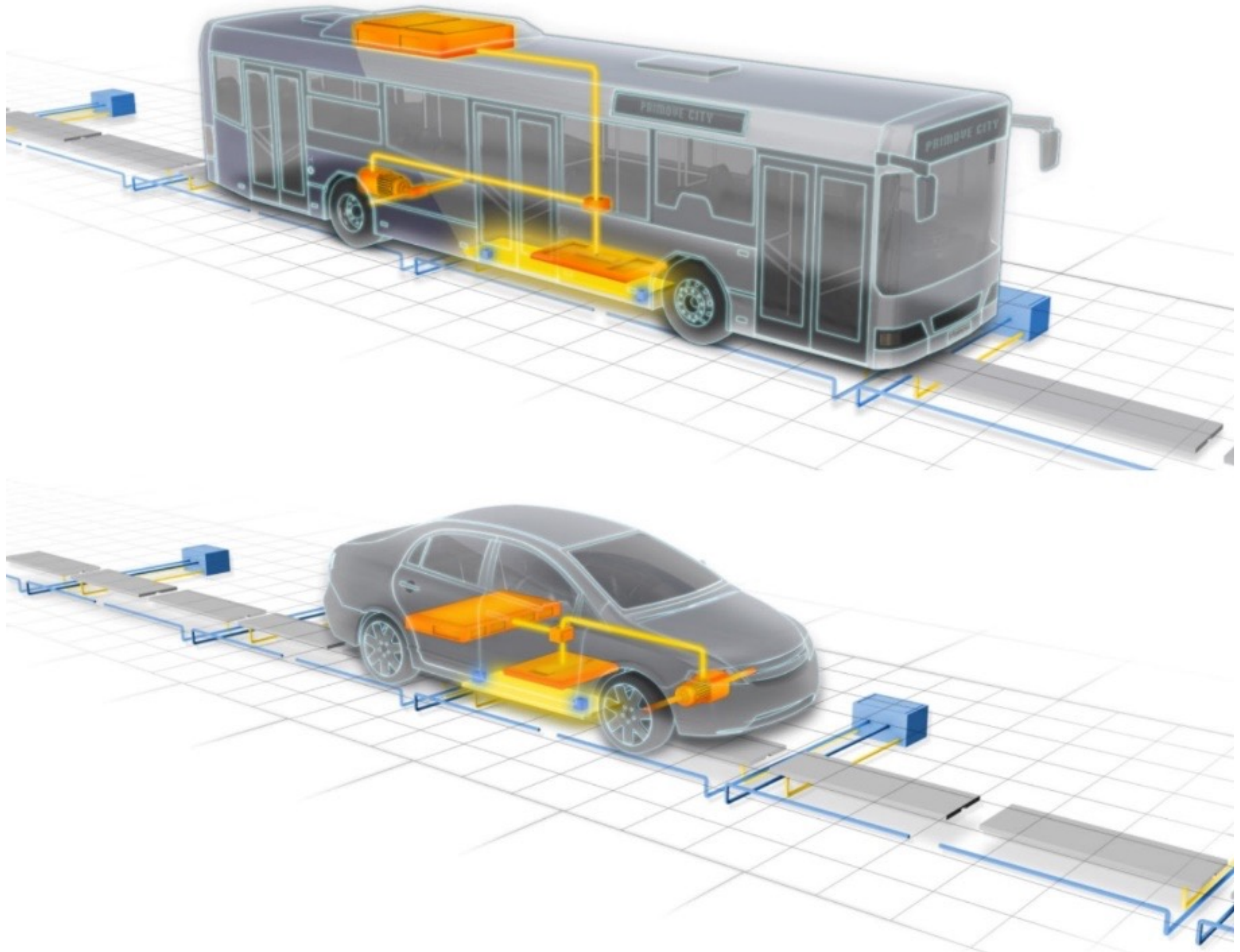


Figure 14: Dynamic wireless power transfer diagram from the IPT PRIMOVE project[39]

4. LITERATURE REVIEW

4.1 Industry literature review

4.1.1 Relevant industry and government reports

Mine electrification is a relatively new topic in the mining industry and academia. In 2017, a report by ARENA[23] discussed energy usage in mining, mining GHG emissions, and how renewable energy can replace fossil fuels. A year later, the Global Mining Guidelines Group (GMG) published a report[9] that provided guidelines/specifications for using battery-supported EVs in underground mine applications. An updated version of this report was produced in 2022[5]. It provides detailed recommendations for considerations in the design of mines, battery electric vehicles, energy storage systems and charging systems. Some of these recommendations are:

1. Detailed considerations in revenue, capital cost, operational cost, and environmental cost are necessary for developing a business case for BEV in existing and greenfield underground mines.
2. Considerations around mine design and operation that include different points in ore/waste handling systems design and the impact of mine layout on that, maintenance areas for BEVs, mobile electric equipment and the required charging facilities, charging methods and connection interfaces, ventilation and cooling systems, and potential fire risks corresponding to BEVs and safety.
3. Information and standards about the BEV's braking system, designing the high-voltage direct current (HVDC) electrical system and other requirements in designing battery electric vehicles.
4. Information and standards about required components, safety, and hazards of batteries in an underground mine.

In 2019, EY published a report based on a survey of mining companies and original equipment manufacturers (OEM) on the challenges and opportunities of mining electrification[16]. Updated reports have been published in subsequent years. Four key themes found by the original survey were:

- electrified mines improve economics and strengthen their licence to operate,
- electrification needs different skills,
- collaboration will unlock better electrification solutions, and
- mine design needs a rethink to build optionality for future innovation.

The "Australia's Emissions Projections 2020"[6] released by the Australian Government provided a detailed discussion of how Australia is positioned to meet its 2030 GHG emissions target. For each major sector, it shows past emissions from 1990 to 2020 and future predictions to 2030. As outlined in Section 1.1, this report strongly suggested automation, electrification, and more aggressive utilisation of renewable energy in the Australian mining industry.

The 2020 VCI State of Play report[8] seeks to understand the drivers and barriers of mine electrification, identify the key enabling technologies and facilitate collaboration to accelerate its adoption using surveys, webinars and interviews. The key conclusions of this report are:

- mine electrification is a foundational enabler for the clean energy transformation of mine sites;
- the economic, health, and environment benefits for businesses leading this transition are enormous, but it comes with its own set of challenges;
- whilst the need for mine sites to shift to electrification is approaching consensus, technology uncertainty remains a significant challenge;
- the mass adoption of electrification technology and storage systems to power mine sites has so far been slow; and
- the industry should focus on collaborating to overcome the barriers beyond the capacity of any individual company to address.

It is clear from these reports that mining electrification is seen as a necessity, not a choice. This is also well recognised by the industry itself[8]. However, fully-electric mine design and operation is unprecedented territory for many miners and OEMs. While some of the technologies may be available in the market from electrification in other industries, e.g., transportation electrification, a whole-of-system approach is needed to lay a feasible and economically viable foundation for mining electrification, develop tools to design and operate fully electrified mines and create plans to train the future workforce for the electric mining operation. Research and development are required to fill the gaps in technology and knowledge, field trials are essential to gain insight into electric mines in real operational environments, and data collection and sharing are critical for achieving net-zero emission mining in Australia and globally.

4.1.2 Relevant organisations for mining electrification

There are several organisations formed to tackle the mine electrification problem. One of the oldest organisations, but not necessarily for mine electrification, is the GMG[40], established in 2012 to bring the global mining community together by providing a platform for collaboration and fostering networking. It aims to facilitate and drive the application, utilisation and development of international mining standards and guidelines and enable a global community and knowledge hub to support these standards and guidelines as positive tools for the worldwide mining industry. As mentioned in the previous section, GMG has published general guidelines on mine electrification that are updated regularly, which are an excellent source of information on the general aspects of mining electrification.

The International Council on Mining & Metals (ICMM)[41] is another relevant organisation that launched the Innovation for Cleaner, Safer Vehicles (ICSV) in 2018. This involves bringing together leading international mining and metals companies and large OEMs to accelerate the development of a new generation of mining vehicles and to improve existing ones. The organisation has three key objectives:

- introducing GHG emission-free surface mining vehicles by 2040;
- minimising the operational impact of diesel exhaust by 2025; and
- making vehicle collision avoidance technology available to mining companies by 2025.

The Electric Mine Consortium[42] (EMC) was formed in 2021, being the most recent organisation, aims to accelerate progress towards a fully electrified, zero-CO_2 and zero-particulates mine. Its members include:

- Miners: Goldfields, South32, OZ Minerals, IGO, Evolution Mining, Newcrest Mining, Blackstone Minerals, Iluka, Sandfire, MMG, Bellevue Gold
- Mining services: Barminco
- OEMs: Epiroc, Zero Automotive
- Battery/storage providers: EnergyVault, 3ME Technology
- Power systems operators: Zenith Energy, Ampcontrol
- Modelling/Consulting: Dassault Systemes, Deswik, Nukon, AWS
- Industry bodies: METS Ignited

EMC launched the Electric Mine Simulation Crowd Challenge[43], led by OZ Minerals, to attract companies and individuals worldwide to propose solutions for developing a scalable electric mine design simulation platform. The Energy Management System Challenge[44] announced in 2022 by the EMC and led by South32 is another example of the efforts to bring together stakeholders to create solutions for electrifying a mine. This challenge is timely because matching energy supply to demand will become more complex in an electric mine than in a conventional diesel-powered mine. However, it presents opportunities to optimise energy costs, efficiency, and carbon emissions. Nevertheless, there are gaps in managing and optimising the energy requirements of an electric mine system, which requires designing a whole-of-system technology solution. The Energy Management System Challenge was seeking solutions and ideas to fill this gap.

The Charge-On Innovation Challenge[45], initiated in 2021, was a global initiative to develop concepts for large-scale haul truck electrification systems to help the mining sector reduce its diesel fuel consumption and significantly cut emissions from surface mine operations. Its members include:

— Miners: BHP, Rio Tinto, Vale, OZ Minerals, South32, Boliden, Teck Resources, Roy Hill, Freeport-McMoRan, Goldfields, Codelco, YanCoal, Antofagasta, Syncrude, Newcrest Mining, Harmony, Citic Pacific Mining, Evolution Mining, Barrick
— Mining services: GHD, Thiess, Mineral Resources
— Industry bodies: Austmine

They announced eight companies as the winning technology innovators in 2022: ABB, Ampcontrol and Tritium (Australia), BluVeinXL, DB Engineering & Consulting (DB E&C) and Echion Technologies, Hitachi Energy, Shell Consortium, Siemens and 3ME Technology. The winners will collaborate with interested mining companies, OEMs and investors to accelerate the technology development to support the future rollout of zero-emission fleets.

The Komatsu Greenhouse Gas Alliance[46], also started in 2021, seeks collaboration to trial Komatsu's pre-production vehicles and offers the option to be the first buyers of the solutions once they are commercially available. The founding members are Rio Tinto, BHP, Codelco and Boliden.

The wide range of recent developments discussed above shows the mining sector's commitment to electrification in the shortest possible timeframe. Most of these efforts are in their early stages, and there is limited information available about their approaches for mine electrification at this point.

4.1.3 Electric mining equipment

Although the history of cable-tethered mining EVs dates back 50 years, modern battery-operated mining machines have been developing since 2015, and major electrically/battery-powered mining machines have been emerging in the market in recent years.

Table 3 shows an example of an electric mining fleet for an underground mine with possible battery capacities and the resultant range for a 15% grade. The "resultant range" refers to the distance an electric mining fleet can travel on a single charge, factoring in elements such as the grade of the terrain (15% in this example) and the battery capacity. This table highlights the variety of vehicles utilised in mines and that these vehicles are typically much larger and heavier than commercial electric vehicles, thus presenting significant challenges in terms of operating range. Below is a summary of the existing or emerging electric equivalents on the market and their characteristics.

TABLE 3. EXAMPLE OF MINING FLEET EV WITH POSSIBLE BATTERY CAPACITIES AND RESULTANT RANGE[9]

EQUIPMENT	FLEET	POWER (KW)	LOADED WEIGHT (KG)	BATTERY (KWH)	RANGE FOR 15% GRADE (KM)
Haulage/water trucks	8	300	60,000	400	8
LHD machines	14	250	60,000	200	4
Graders	1	100	20,000	200	12
Drill and bolters	12	125	25,000	100	4
Emulsion loaders	4	150	15,000	100	8
Large utility vehicles	15	150	15,000	100	8
Small utility vehicles	30	100	5,000	50	12

Graders: MEDATECH has converted a CAT 12M3 Grader for underground mining applications to an electric one[47]. It uses high energy density lithium-ion batteries with a liquid-cooled battery thermal management system. It also has a mobile onboard battery charger instead of multiple charging stations to charge the battery, hence, this technology offers higher flexibility.

Drill and bolters: Epiroc, in collaboration with Swedish construction company Skanska, will develop a battery electric surface drill rig, which will be based on the design of SmartROC T3548. The new electrified version will be known as SmartROC T35 E, and enable zero-emission surface drilling. According to the manufacturer, the electrified drill rig will come with a range of smart features and enhanced automated solutions for optimal performance, safety, and reliability.

Light 4WD vehicles: These are one of the easiest mining vehicles to electrify due to their small size and similarity in energy storage and power rating to standard passenger vehicles. Some examples are:

— Voltra eCruiser EV (see Figure 15) is an electric vehicle launched in 2017 based on the Toyota LandCruiser 70 series, a popular light vehicle used in mining. Its range is about 80-100km. It was trialled at BHP's Olympic Dam site in 2018[49].
— Safescape's Bortana EV[50] (160kW, 350Nm, 2-tonne payload) uses a 3ME lithium-ion battery. It offers a 25kW onboard AC charger (2hrs), or 80kW+ offboard DC charger for faster charging. It was launched in 2019 and has been tested by IGO for underground mining use with positive feedback[51]. See a picture of the vehicle in Figure 15.
— Tembo e-LV cruiser EV[52] (110 kW, 250 Nm) has a 904 kg payload with a battery capacity of 72 kWh and a battery life of 3500 cycles. Its expected range on 0% grade is approximately 200 km. Vivopower conducted its first Tembo e-LV trial at Minexpo Las Vegas in September 2021[53].
— Murray Engineering e-LV[54] (82-110 kW, 300-450 Nm) has a standard 3,200 kg of payload capacity. It has a battery capacity of 40 kWh. The first e-LV of Murray Engineering was launched in May 2021 at the Austmine conference. It uses a lithium-titanium-

oxide (LTO) battery. They partnered with Siemens to develop fast chargers to charge their e-LV in 20 minutes. Goldfields signed up for underground trials[55] at their Granny Smith Mine site in September 2021.

- The RUN-E electric cruiser[56] (90 kW, 200 Nm) has a battery capacity of 35 kWh and a life of 3,000 cycles. This German automotive electronics company has developed various electric drive systems. The RUN-E Electric Cruisers are distributed locally in Australia by Miller Technology. It has an expected life of 300,000 km or 8 years[55].

Explosive charging machines: the Charmec MC 605 VE Smart Drive charger[57], shown in Figure 16, is designed for face and production charging in underground mines with a maximum of 65 m^2 cross-section and a height of 8.8 meters. The emulsion charging kit of 1.5 tonnes is situated at the rear of the machine and includes emulsion mixing, pumping and delivery systems for charging development. This fully EV architecture uses Li-ion batteries, has fast charging capability (40 mins) and uses two high torque direct-drive electric motors. The batteries are charged during the charging process and downhill driving and de-acceleration. Hence, it is expected to increase the total efficiency of operation.

Haul trucks: These trucks typically have payloads between 36 to 450 tonnes. The highest payload versions are referred to as ultra-class and have a payload capacity of 270 tonnes or greater. Most existing haul trucks are diesel-electric in design. They have a diesel engine driving an electric generator, which in turn powers the electric motors that drive each wheel. While this configuration of using electric wheel motors allows convenient modification to be battery-electric, they are one of the most challenging mine vehicles to electrify due to their large size, which implies high energy storage capacities and power ratings. Some examples of the existing fully-electric haul trucks in the market are:

- Kuhn Schweiz eDumper[58] (65 tonne payload) was introduced in 2019. It has 600kWh of battery capacity and a 634kW synchronous motor. A picture of the truck is shown in Figure 17.
- Anglo American is developing an ultra-class electric mining haul truck[59] with a hybrid hydrogen fuel cell and lithium-ion battery with a capacity of 1000kWh.

Figure 15. Example electric mining light 4WD vehicles: eCruiser (left) and Bortana (right)

Figure 16: Charmec MC 605 VE SmartDrive

Figure 17. Electric dump trucks: eDumper

Initial testing was held in 2021.

- Komatsu started the development of a hydrogen-powered electric heavy-dump truck in 2021. It is expected to hit the market by 2030[60].
- Epiroc MT42 Battery truck[61] (42 tonne payload), see Figure 18, is an underground haul truck with improved incline speeds, dump cycles, and hence increased overall productivity. The drivetrain has been optimised to reduce the losses and number of components. Each axle on this truck has a connection to one high-power electric motor. The electrical drivetrain provides higher speed on grades up and down the ramp. A separate single auxiliary motor powers the hydraulic functions, which deliver hydraulic power on demand. According to the manufacturer, extended battery autonomy is achieved through energy regeneration and high energy density battery design.
- Sandvik TH550B battery truck[62] (50 tonne payload), see Figure 19, and Sandvik TH665B truck[63] (65 tonne payload), see Figure 20, use lithium-iron phosphate batteries featuring a "self" battery swapping system which can be controlled by the truck operator without leaving the equipment cabin and only takes a few minutes. These trucks can achieve higher ramp speeds and complete a shorter haul cycle due to the high torque and power delivered by the electric drivetrains.

Loaders: They are generally used to move stockpiled materials to load a haul truck or to deposit the materials in an excavation.

- Sandvik battery LH518B underground loader[64] (18 tonne), as shown in Figure 21, is the most compact 18-tonne loader BEV on the market. The LH518B has a high payload capacity and uses lithium-iron phosphate batteries.

Figure 18: Epiroc MT42 battery minetruck

Figure 19: Sandvik TH550B underground electric truck

Figure 20: Sandvik TH665B underground electric truck

Figure 21: Sandvik LH518B electric loader

— Epiroc manufactures underground loaders for electrified use (Scooptram EST2D, EST3.5 and EST1030) and battery-powered (Scooptram ST7 and ST14)[65]. These vehicles' high energy density batteries are easily swappable for continuous applications. Epiroc ST14 battery underground loader66 (14 tonne), as shown in Figure 22, has a high-power traction motor providing fast tramming and features quick battery swapping.

Drill rigs and jumbos: Jumbos are machines used for drilling and blasting in underground mines to create large openings. Underground drill rigs, however, are smaller and more versatile and are used for drilling smaller holes in mines for ventilation, ore pass, and production drilling. These machines drill holes into rock into which explosives are inserted and detonated. This allows underground tunnels to be created and ore bodies to be removed. These vehicles are modular, which means they can be dismantled, transported to another location, and reassembled.

— Sandvik DD422iE Drill Rig[67], as shown in Figure 23, is an electric mining jumbo connected to the mine power system at the drilling location and has batteries to allow movement to different parts of the mine. According to the manufacturer, the major benefits of this electric drill rig include zero emissions during tramming and improved productivity and contribution to underground workers' health and safety. It can draw reserve power from the batteries during peak loads of drilling. The driveline technology enables the battery to recharge during the drilling cycle using the mines' existing infrastructure. It also recharges while tramming downhill by utilising energy generated by the braking system.

Figure 23: Sandvik DD422iE Drill Rig

As shown above, only a few mining BEVs are currently available in the market, some of which are converted from diesel. Based on the experience from domestic transportation electrification, a ground-up design of BEVs could help to both reduce the cost and to better realise their potential in operation. Also, the industry needs more OEMs to develop BEVs for mining applications. This will likely increase the competition and bring the final cost down for the end-user. Also, innovative business models are necessary to share the risk of battery cost and early failure/end-of-life between the manufacturers and mining companies.

Figure 22: Epiroc Scooptram ST14 battery loader

4.1.4 Best practice in battery utilisation

Various battery technologies have been used in EVs and islanded or grid-tied microgrids. In the transportation domain, domestic EVs have significantly advanced in recent years. According to the Electric Vehicle Council of Australia[68], in 2021, 33 models of hybrid and full electric passenger cars (sedan and SUV) were available in the market in Australia. Among the various technologies, lithium-ion batteries (LIBs) dominated the market due to their high power-to-weight ratio, high energy efficiency, acceptable high-temperature performance, low self-discharge, and the potential for recycling most of their components. However, the cost of material recovery remains challenging for the industry[69]. Other types of batteries that were previously used in passenger vehicles include[70]:

— Sodium sulphur batteries (Na-S) in Ford Ecostar in 1992-93
— Lead-acid batteries (Pb-PbO_2) mostly in forklifts and golf carts and Nickel-metal hydride in GM EV1 in 1996-1999
— Zinc-bromine batteries (Zn-Br_2) in Modec EVs in 2006

TABLE 4. CHARACTERISTICS OF EV BATTERIES[70]

	Pb-PbO_2	Ni-Cd	Ni-MH	Zn-Br_2	Na-NiCl	Na-S	Li-Ion	LEAD-ACID
Working Temperature (°C)	-20-45	0-50	0-50	20-40	300-350	300-350	-20-60	-35-45
Specific Energy (Wh/kg)	30-60	60-80	60-120	75-140	160	130	100-275	30-40
Energy Density (Wh/L)	60-100	60-150	100-300	60-70	110-120	120-130	200-735	80-90
Specific Power (W/kg)	75-100	120-150	250-1000	80-100	150-200	150-290	350-3000	180
Cell Voltage (V)	2.1	1.35	1.35	1.79	2.58	2.08	3.6	2.1
Cycle Durability	500-800	2000	500	>2000	1500-2000	2500-4500	400-3000	<350

Table 4 compares possible battery types for vehicles based on their operational characteristics and durability. It starts with lead-acid batteries, one of the oldest rechargeable battery types, and finishes with lithium batteries, the most commonly-used vehicle battery today. Figure 24 also compares the same battery technologies based on cycle durability (lifetime) and energy density. It is clear that lithium batteries offer superior performance for transportation applications. While the chart only shows lithium-ion batteries, there are several different types of lithium batteries that offer a trade-off between energy density, power density, cost and safety. For transportation applications, lithium-iron phosphate shows promising characteristics, particularly in situations where safety is a higher priority, such as in underground mines. It should be noted that for stationary energy usage, energy density is less important than other factors such as lifetime, cost and reliability etc.

Additionally, the specific energy of LIBs is still much lower than diesel's specific energy density, which is about 14,000 Wh/kg, more than 50 times the most energy-dense lithium batteries. Taking into account the higher efficiencies of electric machines compared to diesel engines, the ratio reduces to about 15 to 20 times. Therefore, having enough battery onboard a BEV should be balanced with the battery unit's cost, weight and volume to minimise the impact on the vehicle's performance and productivity. This is particularly important when selecting the most appropriate charging technology (e.g., battery swapping, fast charging and trolley-assist charging) for high-energy applications such as haul trucks. A combination of swapping, partial fast charging and trolley-assist charging could help compensate for the lack of high energy density of the LIBs compared to diesel. In addition, hauling trucks require high power at times. Considering the limited C-rate of LIBs, a thorough investigation among existing LIBs is needed to choose the one with the highest power capability. That would help compensate for the lack of high energy density too.

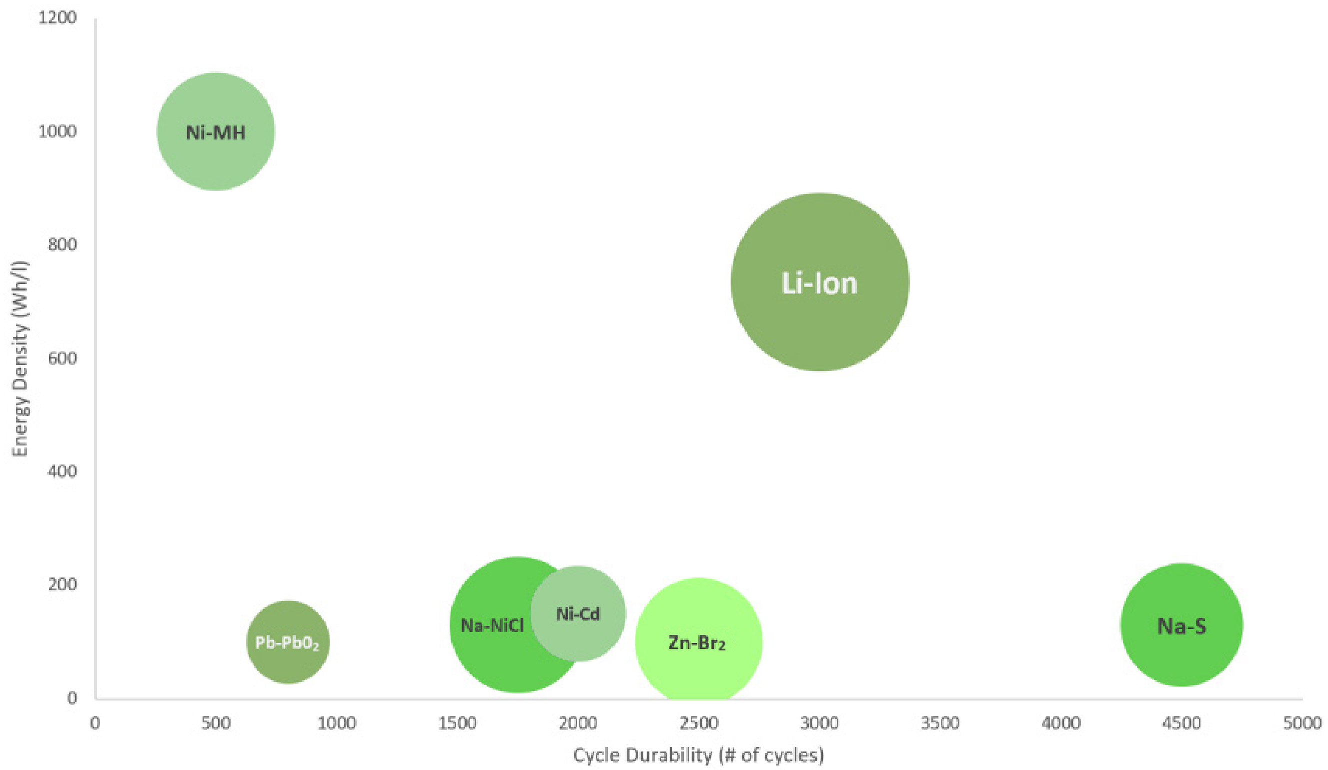


Figure 24. A comparison of battery technologies in terms of their cycle durability (x-axis), energy density (y-axis), specific energy (bubble size), and working temperature (bubble colour). Note that warmer colours represent higher working temperatures[70].

In comparison with LIBs, supercapacitors (SCs) can be charged much faster. SCs can also operate in a broader temperature range. They can provide hundreds of thousands cycles with negligible losses. Their energy density (kWh/kg) is lower than LIBs but their power density (kW/kg) is much higher than LIBs. Furthermore, SCs are more environmentally friendly and made from more abundant materials than LIBs. They are, also, safer than LIBs in terms of fire or explosion. However, they suffer from fast self-discharging and cannot hold energy for long time. In addition, they have limited energy storage capacity.

Currently, there is no global standard for the application of batteries in the mining industry. However, GMG Group has published a document recommending some practices for battery utilisation in underground mining[5]. However, in the domestic electric vehicle industry, numerous standards apply to EV batteries for performance and safety tests[72]. Some of these standards can also be adopted for the mining application, but they may need to be modified to accommodate the likely higher power and larger battery sizes. For example, battery performance tests are designed for domestic applications for charging at lower power ranges, which would be different for mining applications. Another example is battery life testing, designed for low-power charge and discharge regime that would not be the case in the mining application.

For microgrid applications, significant research has been done in the domestic and industrial environments, e.g., microgrid control[73], protection[74], power balancing[75], stability[76], energy management systems[77], and techno-economic analysis of microgrid application for rural electrification[78]. Microgrid business models and value chains have been explained thoroughly[79]. Additionally, practical aspects of the microgrid operation and outstanding issues have been evaluated in numerous studies[80,81]. Assessing existing microgrid projects worldwide, as listed in Table 5, would provide valuable insights and lessons from practical implementations of microgrids. This requires further investigation of the topic and assessment of the reports.

There are also technical documents on the best practices for microgrid design and testing of domestic and small industrial applications such as the report by the Schatz Energy Research Center[82]. In terms of microgrid control, the IEEE 2030.7-2017 standard is available that specifies microgrid controller requirements[83]. This standard mainly covers the energy management system for grid-tied or autonomous operation. In other work[84], 23 distributed generation and microgrid standards have been analysed. Among these standards, 18 correspond mainly to distributed generation, while five introduce the microgrid concept.

Table 5 provides a detailed account of the operating modes and transitions observed in various microgrid projects globally. By studying these projects, we can gain insights into the key design characteristics and control functions that are necessary to ensure the economic, reliable, and secure operation of microgrids at mine sites to provide electricity for BEVs charging. These findings can also help us develop and adapt industry standards for mining power systems, which will be dominated by renewable energies and battery storage systems.

TABLE 5. SUMMARY OF THE APPLICATIONS OF SELECTED MAJOR MICROGRID PROJECTS[81]

MICROGRIDS	OPERATING MODES					TRANSITIONS				
	ON-GRID	OFF-GRID	ALERT STATE	EMERGENCY STATE	BLACKOUT	BUMPLESS ISLANDING	EMERGENCY ISLANDING	SYNCHR	BLACKSTART	
									ON-GRID	OFF-GRID
KERI Microgrid		✓								
Korea-KEPRI Microgrid	✓									
Huatacondo		✓								
Continuon's MV/LV facility		✓								
Am Steinweg	✓									
Eigg Island Project		✓								
Kythnos		✓								
Smart Polygneration Microgrid	✓									
DeMoTec	✓	✓								
Bornholm Island		✓			✓			✓		✓
NTUA	✓	✓				✓		✓		
Hydro Quebec	✓	✓				✓		✓		
BC Hydro	✓	✓				✓		✓		
University of Manchester Microgrid	✓	✓					✓	✓		
Bronsbergen Holiday Park	✓	✓			✓		✓	✓		
CESI Ricerca DER	✓	✓			✓		✓	✓		
CERTS	✓	✓			✓		✓	✓		
Sendai Project	✓	✓			✓			✓		✓
Prince Lab	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Currently, there are no industry standards for the design and operation of microgrids in mining. However, the standards from domestic and industrial microgrids can be adapted for mining operations, with necessary modifications to align with standard mining practices. This requires a thorough assessment of factors such as load requirements, inrush currents, harmonic distortion, starting and stopping of typical mining loads, etc. For grid-connected microgrids the power requirements would be set by the utility provider, e.g. Western Power.

4.2 Patent search

4.2.1 Australian patents

An initial patent search at AusPat[85] has been done using the following keywords:

- **Electric trucks:** This keyword returned seven results. One patent registered by Caterpillar had expired in 2009 because it was not used, claimed, or renewed. Three patents dating back to the 1960s pertained to improved electric components for trucks and lifts, which are irrelevant to the MOVE project. The remaining two patents filed in 2020 developed a system for gravitational energy storage using dump trucks.
- **Electric haul truck:** It returned four results. Three of these patents belong to Siemens and have either ceased or lapsed. The last patent, filed in 2019 by Artisan Vehicle Systems, is about designing a 50-metric-tonne haul truck for underground mining. However, this patent focuses on the truck's design, which differs from the scope of the MOVE project.
- **Truck scheduling:** Only one result was found. It relates to a general truck scheduling system, which expired in 2009 and did not specifically address the unique requirements of mining haul trucks.
- **Battery management system (BMS): T**his keyword returned only one result developed for battery management, which was irrelevant to this work. While battery management is essential for the safe and seamless operation of BEVs, commercially available BMSs should be able to meet the requirements of mining BEVs. Also, the BMSs designed for domestic EVs are likely a viable solution for electric haul trucks.
- **Electric vehicle management:** This keyword returned 28 results. Most patents are related to battery management solutions (e.g., power, thermal, data and communication etc.) within EV battery packs (mostly domestic vehicles). The solutions are mainly developed to manage battery operation during a trip. Among them, 18 patents ceased or lapsed.
- **Electric vehicle:** As expected, this keyword returned 1,692 results. Most of the patents are about battery pack design, electric motor and brake design, thermal management design, charger (wireless and wired) design, communication approaches between different components in a BEV, monitoring systems, regenerative braking, and the onboard battery configuration. These patents do not appear directly relevant to our project, although these components are used in mining BEVs.
- **Energy management system (EMS):** 584 records were found for this keyword. There are patents on energy management systems for microgrid operation and demand response programs that are not directly related to the MOVE project. However, some of the components may be similar. They are not directly related because our EMS will manage the charging infrastructure operation alone and co-optimise the charging infrastructure and backbone energy infrastructure together to exploit the flexibility in both systems towards minimising the overall operation cost. Therefore, a more comprehensive patent search and assessment may be needed for this keyword.
- **Hybrid energy system:** This keyword returned 173 results. Most of the patents under this keyword were found irrelevant to mining applications. However, there are patents on designing a hybrid energy system to power microgrids and EV charging stations. Based on the operation requirements under electrified trucks, hybrid energy system sizing algorithms are needed.
  An in-depth exploration of the relevant patents under this keyword may be helpful. This should be done by considering the substantial differences in energy system design for a mine site. In one patent[86], the design of a hybrid energy system is proposed for electric mine machinery, which is a simple energy management system.
- **Mining vehicle scheduling:** no results returned.
- **Electric vehicle scheduling:** no results returned.

4.2.2 International patents

Based on the Australian patent office recommendation, we searched WIPO IP Portal for international patents. This database contains 4.5 million published international patent applications. A country by country patent search has not been conducted in this report.

- **Electric mining truck:** 342 records were found. Among these records, approximately 71% (244 records) focused mainly on various components of an electric mining truck, such as power supply systems, engines, and thermal management systems. Two noteworthy patents were identified from Siemens and Caterpillar with similar purposes, namely "system and method for reinjection of retard energy in a trolley-based electric mining haul truck" and "control strategy for providing regenerative electrical power to trolley line in trolley capable mining truck". These patents represent efforts to develop trolley systems that can harness energy from mining trucks, and were filed in 2012 and 2013.
- **Electric haul truck:** The keyword search yielded 36 records that covered the 40-tonne capacity Artisan electric truck, as well as multiple international versions of the previously mentioned Siemens patent. Most of the existing patents related to this keyword and the previous one pertain to mining electric truck hardware components. However, it is worth noting that there is a lack of patents that specifically address the development of software for systematic design and electric fleet scheduling. This gap in the market presents a valuable opportunity for development of innovative solutions.
- **Electric Truck scheduling:** This keyword has returned 15 records. None of the patent applications under this keyword was related to electric truck scheduling. However, the electric truck scheduling system along with energy and charging management are completely different from scheduling tools for diesel-operated trucks or other electric semi-mobile vehicles.
- **Mining electric vehicle scheduling:** This keyword has returned 13 records in total. Other than scheduling algorithms for diesel and hybrid mining vehicles, some patents in this list dealt with domestic transportation or semi mobile mining vehicles (e.g., stripping shovel). There was a patent on an intelligent power delivery system design for a hybrid diesel-electric mining vehicle. However, charging and operational scheduling were not discussed in the patent.
- **Electric truck management:** This keyword returned 311 records. These generally focussed on the management of electric vehicle energy, batteries or thermal operation, or else focussed on specific types of electric trucks such as forklift trucks (15 records), garbage trucks (11 records) etc. There were 10 records which dealt with mining vehicles and these included work on: trolley assist systems, fast charging, autonomous operation, thermal management and dispatching systems. The two patents on mine dispatching systems, one by Shoudo Iron and Steel Co, China in 1993, and the other by State Grid Co, China in 2019, cover means for scheduling, dispatching and recording the operation of mining vehicles.
- **Truck energy management system (EMS):** The keyword returned 204 records in total. Most of the patents developed power and energy management system onboard the truck to operate the battery safely and efficiently. An energy management system for a fleet of trucks that accounts for the backbone energy production and storage availability has not been found.
- **Energy management of electric fleet:** This keyword returned 28 results. Three patents were dealing with the management of charging a fleet of domestic electric vehicles. One patent offered charging optimisation of an electric bus fleet. While domestic fleet charging management has similarities with the mining trucks, the differences are enormous and challenging in a different way, which requires significant changes in the design of the algorithms. Other patents mainly developed smart charging methodologies for fast electric vehicle chargers or predictive methods to estimate required charging power.

The Australian and international patents search shows a wealth of technologies and innovations in terms of components onboard electric mining/haul trucks or in a power supply system. However, we couldn't identify patents on the charging infrastructure and onboard battery sizing, or operation of a fleet of electric mining trucks considering battery charging.

4.3 Research publication search

4.3.1 Modelling of electric haul-trucks for mining

Some examples of literature regarding modelling electric haul trucks for mining include the following. Cunanan et al[87] presents the mechanism, performance metrics and recent developments of heavy-duty electric vehicles. Cruzat et al[88] highlights the significant loss mechanism for haul trucks is the resulting rolling resistance between the truck tires and the mine road. Yin et al[89] simulates the dynamic operation of electric drives of mining trucks and obtains the output torque of the traction motor. Cruzat et al[88] develops an integrated electro-mechanical truck model of a haul truck, simulating a hybrid diesel-electric truck model, including components such as powertrain, traction and retarding systems leading to determine the travelling time and daily hauling capacity for given payload and road properties.

4.3.2 Charging technology selection

In the research literature, there are several studies covering mining vehicle electrification. However, none of them has investigated the optimal charging technology selection and electrified haul truck scheduling problem in detail. Rafi et al[90] studied the required cost and productivity of battery swapping and fast-charging technologies for a battery-powered underground haul truck, where multiple battery sizes are considered. However, the proposed model was not used to select the optimal charging technology mix. Cruzat et al[91] described a tool for modelling and evaluating the performance of trolley-powered electric haul trucks is presented, which enables quantification of productivity, energy consumption, and fuel savings. Mareev et al[92] provides a framework for analysis of the energy consumption, required battery size, and life cycle cost of heavy electric vehicles for long-haul transportation, where the necessary fast-charging infrastructure is also considered for the life cycle cost analysis. This study shows that the life cycle cost of heavy-duty electric trucks and conventional diesel trucks can be similar. In further work the same authors[93] investigated the life cycle cost for heavy-duty electric trucks by considering the overhead trolley assist technology. This study also shows trolley-powered electric trucks' competitiveness with conventional diesel trucks.

Mining electrification is a relatively new topic to the research community. However, numerous studies investigated the electrification of heavy-duty vehicles like electric buses. Different scheduling problems have been investigated for the electrification of bus transit, including charging technology selection and placement, charging, electric bus service scheduling, and sizing the required fleet and the battery capacity, which is reviewed[94]. Chen et al[34] investigated the cost competitiveness of multiple optimally designed charging infrastructures for supplying an electric public bus transit system. To find the optimal design for each charging technology, the article considers electric bus fleet size, battery size, charging needs of the transit system, the service frequency, and the required cost for the charging infrastructure. While the operation of haul trucks in a mine site is significantly different, these algorithms can be studied as a stepping stone towards developing the ones for mining applications.

4.3.3 Scheduling of haul-truck charging

Energy management and charge scheduling have been studied rigorously with respect to domestic electric vehicles. Scheduling methodology and mathematical foundation of integrating EVs into power grids have been reviewed[95]. A state-of-art review of the scheduling methods to incorporate EVs concerning different computational optimisation methods for scheduling has been done[96]. Lithium-ion battery and PEM fuel cell technologies and their application for the powertrain of heavy-duty trucks have been investigated[97]. In most studies, battery degradation is included in the formulation to account for fast charging/discharging that exacerbates the battery degradation. This is explained in more detail in Section 3.3.

Nevertheless, some considerable differences exist between electric haul trucks and domestic EVs. In domestic EVs, customer, electricity retailer, and provider satisfaction are critical for an efficient pricing strategy. However, in mines, there is typically one entity that owns the fleet. There is no customer in terms of scheduling for domestic EVs. The vehicle-to-grid (V2G) concept is also likely less significant. However, we will consider it in our study to assess its potential for cost reduction and improving reliability. In domestic EVs, substantial uncertainty exists with respect to different applications, such as traffic congestion, but these uncertainties do not exist in mines at the same level. In the mining operation, the focus is to maintain or improve productivity and hence, for example, the optimal scheduling of haul trucks to minimise cycle times is important. The productivity of a mine can also play a key role in determining the state of charge of batteries in heavy-duty vehicles and can significantly affect the scheduling strategy.

4.3.4 Backbone infrastructure design

An in-depth evaluation of EV charging and grid integration infrastructure has been presented by Das et al[98], who reviews grid integration infrastructure requirements such as power, control and coordination.

Access to electricity is a challenge in remote mine sites. Energy master planning of residential communities and the Net-Zero Planner tool has been developed[99]. While mining operations have a unique load profile and reliability requirements, the knowledge of domestic microgrid sizing and operation can be adopted to some extent. Nevertheless, the energy system design depends on the mine site, and the design may vary significantly from one site to another.

Recently, renewable energy integration into mineral production has been studied[100]. This describes the opportunities and challenges and presents approaches to addressing the problems raised. Microgrid technological development in the US, including planning, performance analysis and software tools for design, have been comprehensively reviewed[101].

In our approach, backbone infrastructure design should be integrated with the mobile fleet design and scheduling to save money with respect to implementing stationary storage. This feature is unique to the mining operations and must be studied in depth.

4.3.5 Relevant software packages

Haul truck simulation packages are powerful and important tools for the mining industry, traditionally used for different purposes for greenfield and brownfield sites. In greenfield sites, these packages can be used for planning and designing mining operations and evaluating different mining scenarios to optimise operations.

In brownfield sites, they provide a safe and cost-effective environment to train operators, optimise haulage operations and evaluate the existing equipment performance. By simulating real-world scenarios, operators can practice in a controlled environment and improve skills while reducing risks. Simulation can also be used to evaluate different haulage strategies and identify the most efficient fleet management. Additionally, simulating different types of haul trucks under various conditions can predict maintenance needs and resolve vehicle conflicts, where the vehicles try to access the same resources or simultaneously operate in the same area.

In the emerging field of mining electrification, haul truck simulation tools can be used to assess the potential benefits and drawbacks of switching to BEVs by simulating and comparing electric and diesel vehicles under a wide range of operating conditions. This will help mining companies to make informed decisions about their electrification plans. Considering the lack of widespread Australian operational experience with electric haul trucks, simulation tools are a valuable option to examine their performance and validate proposed scheduling schemes. This is important for both brownfield and greenfield sites.

Several different simulation software types are available for haul trucks in mining applications, each with its unique features and capabilities. Some of the most popular options include:

- **HxGN MineEnterprise[102]:** Hexagon helps improve efficiency and safety through fleet management by automating processes, optimizing haulage and blending, and providing real-time situational awareness. They integrate data and automate production cycles to reduce costs and raise productivity.
- **HaulSim (RPM Global)[103]:** HAULSIM creates a digital twin of mining operations by connecting vehicle fleet assets, mining plans, and people. It uses a 3D discrete event simulation (DES) engine to accurately represent haulage operations at a mine site. It can quantify the impact of changes on the complex and dynamic nature of a mine site.

- **3DEXPERIENCE GEOVIA (Dassault)[104]:** This platform enables mining companies to create a digital twin of their operation for improved design, simulation, optimization and prediction. This allows for better scheduling and execution in the real world, better understanding, and better outcomes.
- **TruckSim (Mechanical Simulation)[105]:** TruckSim is an advanced simulation tool used to replicate the behaviour of multi-axle commercial and haul trucks in mining. It has over two decades of real-world testing and validation, making it a useful tool for modelling vehicle dynamics, active controllers, performance characteristics and active safety systems.

The MOVE project can utilise these applications in various ways. For example, HaulSim can serve as a simulation platform for multiple haul trucks, considering diesel and electric options, to identify real-world constraints in haulage operations. MineEnterprise can model various types of mining vehicles using CAD designs, while 3DEXPERIENCE offers a platform that combines optimisation, simulation, and digital twin technology. Another alternative for truck modelling is TruckSim, which focuses on vehicle dynamics. These tools can be used to verify the energy consumption of electric trucks in different case studies, obtain a detailed profile for the power requirements of the electric trucks, and benchmark against diesel trucks.

5. CHALLENGES AND TECHNOLOGY GAPS

5.1 Electrification of high-power, high-energy mining vehicles

While battery-electric passenger vehicles are now widely commercially available, there are challenges with electrifying all mining vehicles. Below, some of the challenges are explained.

5.1.1 Energy density

Haul trucks have high power and energy requirements. A major challenge in converting mining vehicles from diesel to battery is the lower energy density of current lithium batteries relative to diesel. Table 6 compares the specific and volumetric energy densities of diesel and lithium batteries, showing the superiority of diesel. On the other hand, battery vehicles are much more efficient in converting stored energy into usable power, and the capabilities of lithium batteries are rapidly improving. Battery vehicles also offer the ability to provide regenerative braking and have lower losses when stationary. This is shown by comparing the effective energy densities of diesel and LIBs in Table 6. Despite this, the required battery size is a key challenge with EVs, affecting both their cost and productivity.

5.1.2 Battery charging

Another key challenge with BEVs is regular charging. As mentioned in Section 3.3.1, various battery charging technologies are available that could be used or repurposed for mining haul truck electrification. However, battery swapping or charging usually takes minutes to tens of minutes, depending on the power level and size of the battery pack. This will adversely affect the site's productivity and cause a slowdown due to the downtime required for battery charging. Also, a high charging power requirements could be a significant burden on the onsite power system requiring a major capital investment.

Choosing the right charging technology or a combination of technologies to deliver power to trucks and machinery is a substantial design task. The required infrastructure must be designed for the desired productivity, with minimum system cost and should offer redundancy to maintain appropriate reliability in the mine operation. The design procedure should also account for the cost of required power system equipment, considering inrush current, harmonics, power quality, etc.

The charging infrastructure design becomes more complicated when the whole of system design, including the backbone energy infrastructure, is considered.

TABLE 6. COMPARISON OF DIESEL AND LITHIUM BATTERIES[9]

	DIESEL		BATTERIES (LITHIUM)	
	NOMINAL	EFFECTIVE CONSIDERING EFFICIENCY	NOMINAL	EFFECTIVE CONSIDERING EFFICIENCY
Specific energy density	50 MJ/kg	15-17.5 MJ/kg	0.9 MJ/kg	0.81 MJ/kg
Volumetric energy density	35 MJ/litre	10.5-12.25 MJ/litre	6.2 MJ/litre	5.58 MJ/litre

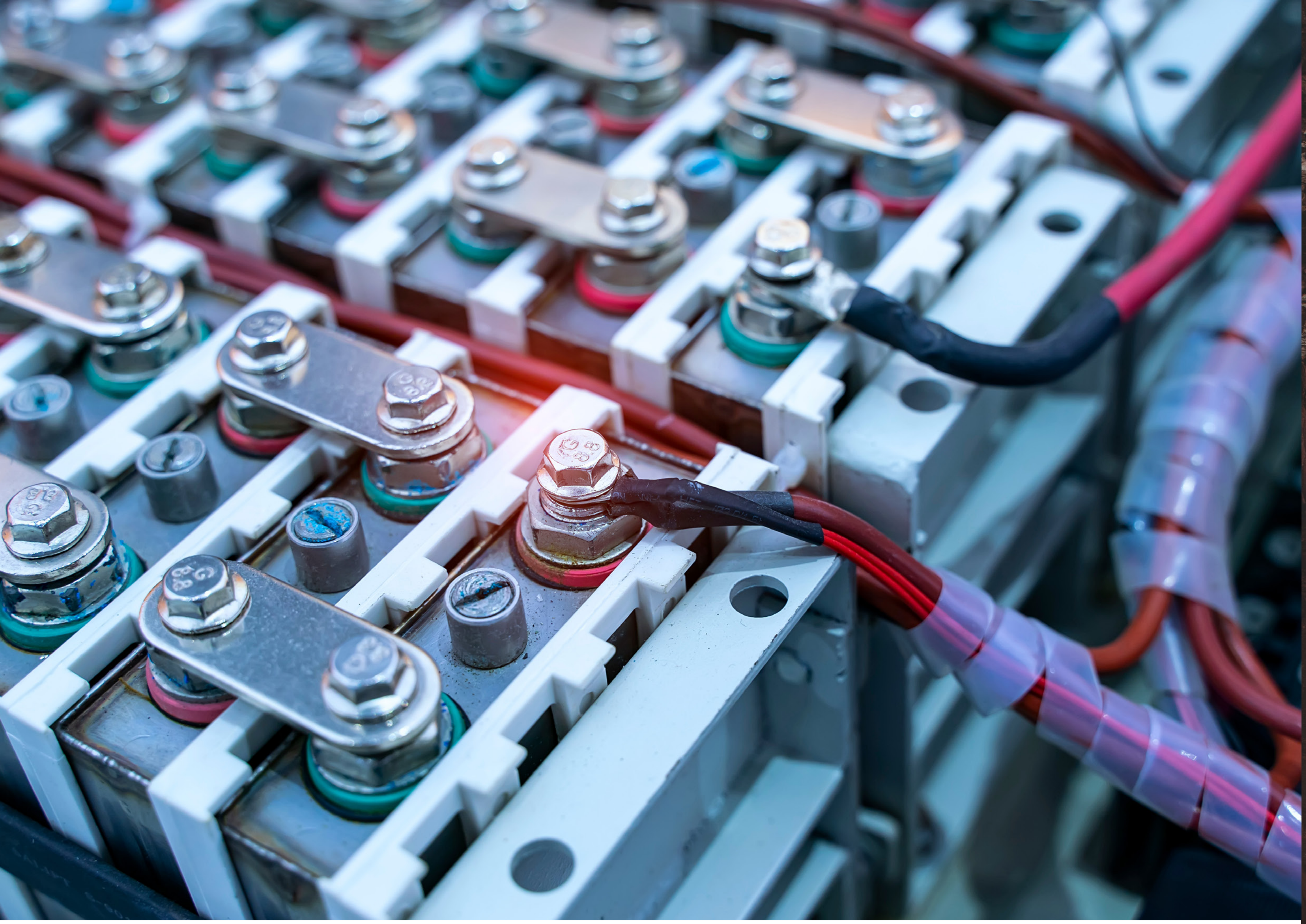
For instance, when available, the design could take advantage of the onboard vehicle batteries for renewable energy storage and reduce the need for large stationary storage devices. This whole of system design approach is expected to reduce the cost of electrification considerably. However, sophisticated algorithms for the design and operation of the system must be developed.

5.1.3 Commercial availability of suitable electric mining vehicles

Due to the energy storage challenges, only a limited number of battery-operated mining vehicles are currently available in the market, as discussed in Section 4.1.3. Most of the existing electric trucks and machinery are converted diesel vehicles with the addition of a battery, charger, and electric motor/generator. As we have seen in domestic transportation electrification, a ground-up EV design is needed to leverage their benefits entirely. It is expected that ground-up designs of new electric trucks and machinery for mining applications will be inevitable in future when a larger market appears for zero-emission vehicles in the mining industry.

5.2 Power system design

To achieve the maximum GHG emission reduction, it is necessary to power the mine from renewable energy sources. However, considering the sporadic and unpredictable nature of renewable generation and the unavailability of PV generation at night, complementary renewable energy sources and energy storage units are required to operate a mine continuously. While a 100% renewable-based power system for a mine is technically feasible, the CAPEX of such solutions could be considerable. To reduce the required capital investment, a trade-off between GHG emissions and energy system costs could be made by deploying smaller diesel or natural gas-powered generators to provide power during low renewable energy generation periods. Depending on the solar and wind resources available in a given area, the capital cost of equipment, cost of fuels and maintenance, a high level of GHG emission reduction could still be achieved. Alternatively, reduced energy storage would be required if a grid connection is available, but this is not the case for many mine sites in Australia.



Some existing mining loads, such as crushers, may have significant time-varying loads. Battery charging (especially fast chargers) can add even more electrical load variations at high power levels, which can significantly affect the power quality in the mine. Therefore, a cautious and detailed assessment of power quality before and after electrification is needed to ensure the safe and reliable operation of the site.

5.3 Electric mine design

A significant part of the existing mine design considers the capabilities and limitations of existing diesel-powered mine vehicles. Given the significant change to BEVs, there are important implications to the design and operation of mines to best utilise BEVs. For example, electrifying all trucks and machinery in underground mines means that a lower level of airflow is needed, and thus a smaller ventilation system is required. This could significantly reduce the time between starting the construction of a mine and first producing ore, which is an important financial metric. Also, electric trucks may be able to carry heavy ore loads faster up steeper slopes than their equivalent-sized diesel trucks. This can be leveraged to maintain the productivity level affected by the charging time delays and even improve productivity compared to diesel vehicles. Additionally, higher ramp slopes would save time and money in the mine construction stage.

In the future, the move towards autonomous vehicles is also important. Eliminating driver labour costs may change the optimal size of mining vehicles away from the current trend of larger vehicles. This means that materials could be moved using a larger fleet of smaller trucks, driven autonomously, travelling at a higher speed. This also can positively impact the mine design (for example, requiring smaller tunnels and pathways) and reduce cost.

5.4 Training

Given the discussion on the changes with the electric mine above, this will significantly affect the mine personnel skill mix. This is discussed in more detail in the EY report[16].

6. CONCLUSION

Electrifying haul trucks and machinery in mining is a crucial transformation driven by economic, environmental, social, and governance considerations. Mining electrification paves the way towards more efficient, sustainable and safer underground and open pit operations. It can also be augmented with new and adaptive technologies such as autonomy, digitialisation, IoT-based communication and data analysis to further reduce costs across the entire mining supply chain, from extraction to transport.

While mine electrification holds many benefits, the transition is complex and multifaceted. It involves the development of new technologies or repurposing existing ones, significant investment in infrastructure and hardware, process changes, and training workers with new skills. Done incorrectly, it could lead to higher costs of operation and lower productivity. Some key questions in this transition that need to be answered include:

1. How can the optimal battery capacity be determined for mining trucks, considering the interaction of cost, volume, weight, charging infrastructure and the mine productivity at a mine site?
2. What is the best approach for recharging the batteries, considering factors such as timing, location, method and impact on the mine productivity, charging infrastructure requirements and overall electrification costs?
3. What energy infrastructure is necessary to generate and deliver electricity to mining trucks, and when and where is it needed?
4. What skills will the workforce of fully-electric mines need? This is a major concern for the industry, as acquiring technology may be quick, but reskilling or training the existing or new workforce can take substantial time for planning, development, and implementation.

In light of the challenges and uncertainties surrounding mine electrification, the MOVE project aims to lead the way by utilising existing, known capabilities (such as battery-supported vehicles, microgrids and battery technologies) to develop site-specific solutions and meet the requirements and map out a clear path towards electrifying mine operations. In particular, the MOVE project aims to do this by providing practical solutions, including modelling and assessment tools and real-world case studies. The project primarily focuses on answering four major questions (listed above) that the industry faces during the transition to reach a more efficient, sustainable and safe future for mining operations. The outcomes of the MOVE project will:

- Empower mining companies to understand the benefits and technical risks, and costs of implementation involved;
- Provide a tailored guide to fit-for-purpose battery size selection for mobile equipment;
- Support decarbonisation efforts for various types of mines and promote "green" mining and production practices with a focus on renewable energy sources (which is the target); and
- Assist battery equipment, technology and service providers to service mining companies during the transition.

The social outcomes are expected to include the ability of mining operations to share green energy with neighbouring communities and to improve the performance of energy systems of remote and urban communities. These outcomes are expected to demonstrate the positive impact of electrified mining on the environment and local communities. This project is expected to propose changes to operations that could improve mining companies' ratings on ethical investment funds.

The commercialisation/impact potential is substantial, as described in the VCI State of Play Electrification report[8]. This project will address and mitigate the risks identified in the VCI report: 'evaluating technology options' and 'understanding economic value' by providing a closer estimate of technology's costs and readiness level. The project will also provide an assessment framework to help mining companies make informed choices when selecting technology options.

7. ENDNOTES

1. Australian Bureau of Statistics. Energy Account, Australia. https://www.abs.gov.au/statistics/industry/energy/energy-account-australia/latest-release.

2. Australian Government. National Inventory Report 2020.; 2020.

3. World Health Organization. Diesel Engine Exhaust Carcinogenic.; 2012.

4. Joint Institute for Strategic Energy Analysis. Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches. https://www.nrel.gov/docs/fy20osti/76156.pdf. Published 2020.

5. Global Mining Guidelines Group. Recommended Practices for Battery Electric Vehicles.; 2022.

6. Australian Government. Australian Emissions Projections 2020.; 2020.

7. Australian Government. Australia's emissions projections 2021. https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2021#:~:text=Under current policies%2C cumulative emissions,Mt CO_2-e in 2030. Published 2021.

8. Ratcliffe MM, Stanway G. State of Play: Electrification.; 2020.

9. GMG Group. GMG Recommended Practices for Battery Electric Vehicles in Underground Mining.; 2018.

10. Lee D-Y, Thomas VM, Brown, Marilyn A. Electric urban delivery trucks: Energy use, greenhouse gas emissions, and cost-effectiveness. Environ Sci Technol. 2013;47(14):8022-8030.

11. Elangovan R, Kanwhen O, Dong Z, Mohamed A, Rojas-Cessa R. Comparative Analysis of Energy Use and Greenhouse Gas Emission of Diesel and Electric Trucks for Food Distribution in Gowanus District of New York City. Front Big Data. 2021;4.

12. World Economic Forum. New Solutions for Mining in the Digital Age.; 2015.

13. EY. ESG with a heightened focus on environment and social issues, emerges as the top risk/opportunity for the mining sector. https://www.ey.com/en_gl/news/2021/10/esg-with-a-heightened-focus-on-environment-and-social-issues-emerges-as-the-top-risk-opportunity-for-the-mining-sector. Published 2021.

14. White & Case. Taking ESG seriously: The crucial role of mining investors in the energy transition. https://www.whitecase.com/insight-our-thinking/taking-esg-seriously-crucial-role-mining-investors-energy-transition. Published 2021.

15. Deloitte. Tracking the trends 2023 The indispensable role of mining and metals. https://www2.deloitte.com/au/en/pages/energy-and-resources/articles/tracking-the-trends.html.

16. EY. Will Electrification Spark the Next Wave of Mining Innovation?; 2019.

17. National Council for Fire and Emergency Services. Incidents involving Electric Vehicles. https://www.afac.com.au/auxiliary/article/incidents-involving-electric-vehicles. Published 2022.

18. NSW Government. Explosion risk of battery units for underground battery electric vehicles. https://www.resourcesregulator.nsw.gov.au/sites/default/files/2023-02/safety-bulletin-sb23-01-explosion-risk-of-battery-units-for-underground-battery-electric-vehicles.pdf. Published 2023.

19. BHP. BHP Annual Report 2021.; 2021.

20. Casey JP. In numbers: how mining became to be Australia's most profitable sector. Mining Technology. Min Technol. 2021.

21. Wikipedia. Mining in Australia. https://en.wikipedia.org/wiki/Mining_in_Australia. Accessed September 14, 2021.

22. Australian Government. Australia's Identified Mineral Resources - World Rankings. https://www.ga.gov.au/digital-publication/aimr2020/world-rankings. Published 2020.

23. ARENA. Renewable Energy in the Australian Mining Sector: White Paper.; 2017.

24. Australian Bureau of Statistics. Energy in Australia 2012-13.; 2014.

25. Australian Government. Australian Energy Update 2020.; 2020.

26. Australian Taxation Office. Fuel tax credit rates for business. https://www.ato.gov.au/business/fuel-schemes/fuel-tax-credits—-business/rates—-business/. Published 2023.

27. Fleet Auto News. Historical ULP and diesel pump prices in Australia. https://fleetautonews.com.au/historical-pump-prices-in-australia/.

28. Australian Government. Resources and Energy Quarterly - December 2022. https://www.industry.gov.au/sites/default/files/2022-12/resources-and-energy-quarterly-december-2022.pdf. Published 2022.

29. Australian Energy Regulator. Gas Market Prices. https://www.aer.gov.au/wholesale-markets/wholesale-statistics/gas-market-prices.

30. AARMI. Reducing EV Charging Infrastructure Costs. hhttps://rmi.org/insight/reducing-ev-charging-infrastructure-costs. Published 2019.

31. Tritium. PK350/350kW Specifications. https://tritiumcharging.com/wp-content/uploads/2023/02/TRI105.DTA_.002_Veefil-PK350-Specifications.pdf. Published 2022.

32. ABB. Electric Vehicle Infrastructure: Terra High Power - Gen III. hhttps://library.e.abb.com/public/43e7e6267afb42ab9730c273092b8ba8/9AKK107991A9632-RevB_Terra_HP_Gen 3_Leaflet.pdf. Published 2021.

33. International Mining. China's CATL sees battery swapping playing a major role in the future of zero emissions mining trucks. https://im-mining.com/2022/04/06/chinas-catl-sees-battery-swapping-playing-a-major-role-in-the-future-of-zero-emissions-mining-trucks/. Published 2022.

34. Chen Z, Yin Y, Song Z. A cost-competitiveness analysis of charging infrastructure for electric bus operations. Transp Res Part C Emerg Technol. 2018;93(June):351-366. doi:10.1016/j.trc.2018.06.006

35. Koellner WG, Brown GM, Rodríguez J, Pontt J, Cortés P, Miranda H. Recent advances in mining haul trucks. IEEE Trans Ind Electron. 2004;51(2):321-329. doi:10.1109/TIE.2004.825263

36. SAE International. Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology.; 2022.

37. SAE International. Wireless Power Transfer for Heavy-Duty Electric Vehicles.; 2022.

38. Unplugged. Wireless charging for Electric Vehicles. http://unplugged.enide.eu/wordpress/wp-content/uploads/2015/12/UNPLUGGED-Publishable-Final-Report.pdf. Published 2015.

39. PT Technology. Dynamic Wireless Charging of Electric Vehicles in Motion. https://ipt-technology.com/e-mobility-wireless-dynamic-charging/.

40. Global Mining Guidelines Group. https://gmggroup.org/.

41. International Council on Mining & Metals. https://www.icmm.com/.

42. Electric Mine Consortium. https://www.electricmine.com/.

43. OZ Minerals. Electric Mine Simulation. https://www.ozminerals.com/en/how-we-work/think-and-act-differently/electric-mine-simulation.

44. Electric Mine Consortium. Electric Mine Consortium Seeking Energy Management System. https://www.electricmine.com/electric-mine-consortium-seeking-energy-management-system/.

45. Charge On Innovation Challenge. https://chargeoninnovation.com/.

46. Komatsu. Komatsu's collaborative customer alliance to advance zero-emission equipment solutions. https://www.komatsu.com.au/company/news-media/news/komatsu-announces-collaborative-customer-alliance.

47. Medatech. Battery Electric Motor Grader Retrofit. https://medatech.ca/case-study/battery-electric-motor-grader-retrofit/.

48. Australian Mining. The world's first battery-electric surface drill rig. https://www.australianmining.com.au/features/the-worlds-first-battery-electric-surface-drill-rig/. Published 2022.

49. Tancredi T. All-electric Voltra eCruiser to cut emissions in mining sites. 4x4 Aust. 2018.

50. Safescape. Bortana EV. https://www.safescape.com/bortana-ev/. Accessed October 15, 2021.

51. Guthrie C. Successful underground EV trial at Nova. Min Mag. 2020.

52. GB Auto. Tembo 4x4 e LV Electric Cruiser. https://www.inspiritconsult.com.au/downloads/Tembo 4x4 e-LV.pdf. Published 2021.

53. Tembo. News. https://temboelv.com/news/.

54. Murray Engineering. Ultra Fast Recharging Battery Electric Vehicle. https://www.inspiritconsult.com.au/downloads/Murray Engineering Battery Electric Brochure 2021 V2.pdf.

55. Inspirit Consulting. Electric light vehicles for mining – what are the options? https://www.inspiritconsult.com.au/blog/2021/06/17/electric-light-vehicles/. Published 2021.

56. Inspirit Consulting. Run E - Electric Cruiser. https://www.inspiritconsult.com.au/blog/2021/06/17/electric-light-vehicles/. Published 2021.

57. Normet. Charmec MC 605 VE SD. https://www.normet.com/wp-content/uploads/2022/01/charmec-mc-605-ve-sd-tds-2022.pdf.

58. Kuhn Gruppe. E Dumper. https://kuhn-gruppe.ch/en/building-machines/products/emining/e-dumper-0.

59. Williams. Williams Advanced Engineering Partners with Anglo American on World's Largest Electrified Mining Truck. https://wae.com/news/williams-advanced-engineering-partners-with-anglo-american-on-worlds-largest-electrified-mining-truck/. Accessed October 19, 2021.

60. Yamanaka H. Komatsu aims for lead in hydrogen-powered mining trucks. Nikkei Asia. 2021.

61. Epiroc. Minetruck MT42 Battery. https://www.epiroc.com/en-au/products/loaders-and-trucks/electric-trucks/minetruck-mt42-battery.

62. Sanvik. Sandvik TH550B. https://www.rocktechnology.sandvik/en/products/underground-loaders-and-trucks/battery-electric-loaders-and-trucks/th550b/.

63. Sandvik. Sandvik TH665B. https://www.rocktechnology.sandvik/en/products/underground-loaders-and-trucks/battery-electric-loaders-and-trucks/th665b/.

64. Sandvik. Sandvik LH518B. https://www.rocktechnology.sandvik/en/products/underground-loaders-and-trucks/battery-electric-loaders-and-trucks/lh518b-battery-electric-loader/.

65. Epiroc. Underground electric loaders. https://www.epiroc.com/en-ke/products/loaders-and-trucks/electric-loaders.

66. Epiroc. Scooptram ST14 Battery. https://www.epiroc.com/en-au/products/loaders-and-trucks/electric-loaders/scooptram-st14-battery.

67. Sandvik. DD422iE Development drill rig. https://www.rocktechnology.sandvik/en/products/underground-drill-rigs-and-bolters/mining-jumbos/dd422ie-development-drill-rig/.

68. Electric Vehicle Council. Passenger Vehicles. https://electricvehiclecouncil.com.au/about-ev/evs-available/. Published 2021. Accessed December 2, 2021.

69. US Department of Energy. Batteries for Hybrid and Plug-In Electric Vehicles. https://afdc.energy.gov/vehicles/electric_batteries.html. Accessed December 2, 2021.

70. Sanguesa JA, Torres-Sanz V, Garrido P, Martinez FJ, Marquez-Barja JM. A Review on Electric Vehicles: Technologies and Challenges. Smart Cities. 2021;4(1):372-404. doi:10.3390/smartcities4010022

71. Horn M, MacLeod J, Liu M, Webb J, Motta N. Supercapacitors: A new source of power for electric cars? Econ Anal Policy. 2019;61:93-103. doi:10.1016/j.eap.2018.08.003

72. Castillo EC. Standards for Electric Vehicle Batteries and Associated Testing Procedures. Elsevier Ltd.; 2015. doi:10.1016/B978-1-78242-377-5.00018-2

73. Ahmethodzic L, Music M. Comprehensive review of trends in microgrid control. Renew Energy Focus. 2021;38(September):84-96. doi:10.1016/j.ref.2021.07.003

74. Dagar A, Gupta P, Niranjan V. Microgrid protection: A comprehensive review. Renew Sustain Energy Rev. 2021;149(June 2020):111401. doi:10.1016/j.rser.2021.111401

75. Komala K, Kumar KP, Cherukuri SHC. Storage and non-Storage Methods of Power balancing to counter Uncertainty in Hybrid Microgrids - A review. J Energy Storage. 2021;36(February):102348. doi:10.1016/j.est.2021.102348

76. San G, Zhang W, Guo X, Hua C, Xin H, Blaabjerg F. Large-disturbance stability for power-converter-dominated microgrid: A review. Renew Sustain Energy Rev. 2020;127(March):109859. doi:10.1016/j.rser.2020.109859

77. Raya-Armenta JM, Bazmohammadi N, Avina-Cervantes JG, Sáez D, Vasquez JC, Guerrero JM. Energy management system optimization in islanded microgrids: An overview and future trends. Renew Sustain Energy Rev. 2021;149(June):111327. doi:10.1016/j.rser.2021.111327

78. Veilleux G, Potisat T, Pezim D, et al. Techno-economic analysis of microgrid projects for rural electrification: A systematic approach to the redesign of Koh Jik off-grid case study. Energy Sustain Dev. 2020;54:1-13. doi:10.1016/j.esd.2019.09.007

79. Borghese F, Cunic K, Barton P. Microgrid Business Models and Value Chains. Schneider Electr. 2017:9.

80. Hirsch A, Parag Y, Guerrero J. Microgrids: A review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev. 2018;90:402-411. doi:10.1016/J.RSER.2018.03.040

81. Cagnano A, De Tuglie E, Mancarella P. Microgrids: Overview and guidelines for practical implementations and operation. Appl Energy. 2020;258(November 2019):114039. doi:10.1016/j.apenergy.2019.114039

82. Schatz Energy Research Center. Community Microgrid Technical Best Practices.; 2020.

83. IEEE PES. IEEE 2030.7-2017 Standard for the Specification of Microgrid Controllers.; 2018.

84. Rebollal D, Carpintero-Rentería M, Santos-Martín D, Chinchilla M. Microgrid and distributed energy resources standards and guidelines review: Grid connection and operation technical requirements. Energies. 2021;14(3). doi:10.3390/en14030523

85. Australian Patents - Search. https://www.ipaustralia.gov.au/patents/understanding-patents/searching-patents. Published 2021.

86. Kareemulla T, Gliniorz V, Richthammer B. System for supplying energy to electrically operated mining machines. 2020.

87. Cunanan C, Tran M-K, Lee Y, Kwok S, Leung V, Fowler M. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. Clean Technol 2021, Vol 3, Pages 474-489. 2021;3(2):474-489. doi:10.3390/CLEANTECHNOL3020028

88. Valenzuela Cruzat J, Aníbal Valenzuela M. Integrated Modeling and Evaluation of Electric Mining Trucks during Propel and Retarding Modes. IEEE Trans Ind Appl. 2018;54(6):6586-6597. doi:10.1109/TIA.2018.2854258

89. Yin YM, Yang J, Zhang WM. Handling and Roll Prediction of Electric Drive Mining Trucks. Adv Mater Res. 2013;712-715:1135-1138. doi:10.4028/WWW.SCIENTIFIC.NET/AMR.712-715.1135

90. Rafi MAH, Rennie R, Larsen J, Bauman J. Investigation of fast charging and battery swapping options for electric haul trucks in underground mines. 2020 IEEE Transp Electrif Conf Expo, ITEC 2020. June 2020:1081-1087. doi:10.1109/ITEC48692.2020.9161654

91. Cruzat JV, Anibal Valenzuela M. Modeling and Evaluation of Benefits of Trolley Assist System for Mining Trucks. IEEE Trans Ind Appl. 2018;54(4):3971-3981. doi:10.1109/TIA.2018.2823261

92. Mareev I, Becker J, Sauer DU. Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. Energies. 2018;11(1). doi:10.3390/en11010055

93. Mareev I, Sauer DU. Energy consumption and life cycle costs of overhead catenary heavy-duty trucks for long-haul transportation. Energies. 2018;11(12). doi:10.3390/en11123446

94. Perumal SSG, Lusby RM, Larsen J. Electric bus planning & scheduling: A review of related problems and methodologies. Eur J Oper Res. 2022;301(2):395-413. doi:10.1016/j.ejor.2021.10.058

95. Zheng Y, Niu S, Shang Y, Shao Z, Jian L. Integrating plug-in electric vehicles into power grids: A comprehensive review on power interaction mode, scheduling methodology and mathematical foundation. Renew Sustain Energy Rev. 2019;112:424-439. doi:10.1016/J.RSER.2019.05.059

96. Yang Z, Li K, Foley A. Computational scheduling methods for integrating plug-in electric vehicles with power systems: A review. Renew Sustain Energy Rev. 2015;51:396-416. doi:10.1016/J.RSER.2015.06.007

97. Burke A, Sinha A, Kumar A. UC Davis Research Reports Title Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses Permalink https://escholarship.org/uc/item/7s25d8bc Publication Date Data Availability. March 2020. doi:10.7922/G2H993FJ

98. Das HS, Rahman MM, Li S, Tan CW. Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. Renew Sustain Energy Rev. 2020;120:109618. doi:10.1016/J.RSER.2019.109618

99. Zhivov AM, Case MP, Jank R, Eicker U, Booth S. Planning Tools to Simulate and Optimize Neighborhood Energy Systems. NATO Sci Peace Secur Ser C Environ Secur. 2017:137-163. doi:10.1007/978-94-017-7600-4_8

100. Igogo T, Awuah-Offei K, Newman A, Lowder T, Engel-Cox J. Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. Appl Energy. 2021;300:117375. doi:10.1016/J.APENERGY.2021.117375

101. Feng W, Jin M, Liu X, et al. A review of microgrid development in the United States – A decade of progress on policies, demonstrations, controls, and software tools. Appl Energy. 2018;228:1656-1668. doi:10.1016/J.APENERGY.2018.06.096

102. Hexagon. HxGN MineEnterprise. https://hexagon.com/products/product-groups/hxgn-mineenterprise.

103. RPMGlobal. Haulsim. https://rpmglobal.com/product/haulsim/.

104. Dassault Systemes. GEOVIA R2023x. https://www.3ds.com/products-services/geovia/products/3dexperience-geovia/.

105. Mechanical Simulation Corporation. TruckSim. https://www.carsim.com/products/trucksim/index.php.

106. Wikipedia. Ton. https://en.wikipedia.org/wiki/Ton. Accessed October 19, 2021.

107. CarbonBrief. Factcheck: How electric vehicles help to tackle climate change. https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change/

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