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GMSG RECOMMENDED PRACTICES FOR BATTERY ELECTRIC VEHICLES IN UNDERGROUND MINING

SUBMITTED BY
Underground Mining Battery Electric Vehicles Working Group

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1. FOREWORD

The Global Mining Standards and Guidelines (GMSG) Group is a global, multi-stakeholder community to advance the availability and use of standards and guidelines for the international mining industry. This GMSG document was prepared by a GMSG working group. Draft documents are checked and approved by working group members, prior to approval by the GMSG Governing Council.

Formed as part of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), GMSG is supported by CIM and three other Partner Organizations: the Australasian Institute of Mining and Metallurgy (AusIMM), the Southern African Institute of Mining and Metals (SAIMM), and the Surface Mining Association for Research and Technology (SMART), as well as its Member Companies and participants.

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2. DEFINITIONS OF TERMS, SYMBOLS, AND ABBREVIATIONS

Instructed person*	BEV or charger operator
Skilled person*	BEV and charger maintenance person
AC	Alternating Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
CCS	Combined Charging System
DC	Direct Current
DOD	Depth of Discharge
E-Stop	Emergency Stop
FLA	Full Load Amperage
GF	Ground Fault
LHD	Load Haul Dump (machine)
LIB	Lithium-Ion Battery
OCPP	Open charge point protocol
OEM	Original Equipment Manufacturer
OWHS	Ore / Waste Handling System
SOC	State of Charge
VAC	Volts Alternating Current
VDC	Volts Direct Current
XML	Extensible Markup Language

* See International Electrotechnical Commission (2004)

3. KEYWORDS

Battery electric vehicle, Electric mine, Mine design, Performance standards

4. SCOPE

This guideline outlines the recommended practice for use of battery electric vehicles (BEVs) in an underground mining environment. It is structured as a specification and can be included by mining companies in tender documents to mining vehicle original equipment manufacturers (OEMs). This guideline can serve as a blueprint / path forward for OEM research and development efforts.

The BEV guideline strikes an appropriate balance between standardization and innovation. It allows miners to operate a fleet of BEVs without concerns about proprietary equipment and interfaces. Although the BEV guideline should not impede innovation for OEMs, it leverages and references existing standards and guidelines, including from applicable automotive, electrical, automation, and other industries. These standards and guidelines are recommended only: it is up to the user to select which standards they will use. Standards are cited by name only throughout this guideline. Tables of the recommended standard names and the topics they cover are provided at the beginning of Sections 8–10 to assist guideline users and facilitate updating future guideline editions. Full citations for all published standards are provided in Section 13. BEV technologies are rapidly evolving: the reader is cautioned that new editions of the referenced standards may have been published, and entirely new standards may have been issued since this guideline was released. In order to keep up with this trend, the BEV guideline will be revised and new editions published regularly.

The BEV guideline is structured around seven key components, arranged in a logical sequence for an underground operation considering "going electric". First, at the conceptual stage, it is necessary to determine the charging philosophy, that is, the type(s) of chargers that will be used with the goal of making the recharging and operation of electric equipment as simple, convenient, and safe as refuelling and operating diesel vehicles. Then work can proceed from mine design, through to BEV design, energy storage systems (batteries), charging systems, and performance standards. Finally, because it is global in scope, mining companies and OEMs throughout the world should be able to use this guideline, while at the same time acknowledging that regional differences exist in terms of standards and regulatory frameworks.

5. GENERAL BACKGROUND

Most underground mining operations use diesel-powered trackless mobile machines (vehicles), defined by Mine Health and Safety Inspectorate (2015) of South Africa as "any self-propelled mobile machine that is used for the purpose of performing mining, transport or associated operations underground or on surface at a mine and is mobile by virtue of its movement on wheels, skids, tracks, mechanical shoes or any device fitted to the machine”. As battery technology advances, benefits will accrue for replacing diesel-powered trackless vehicles with BEVs in underground mining operations.

In commercial truck fleets, battery technology was shown to be economically viable if the benefits of lower greenhouse gas and other emissions and lower operating and maintenance costs matched or outweighed the costs, namely high procurement cost and limited range (Feng & Figliozzi, 2012). Electric buses completely powered by on-board batteries offer similar benefits over diesel-powered buses, and eliminate the need for infrastructure to obtain power from powerlines above or below the bus, unlike trolleys and gapbuses, respectively. Battery electric cars for personal use are more expensive than gasoline- or diesel-powered cars and require fixed charging infrastructure. Battery electric commercial trucks, cars, trains, and buses are generally far more efficient than their internal combustion engine counterparts. As an additional benefit, they can further increase efficiency by using regenerative braking to convert kinetic energy into potential energy, which can then be re-used when later accelerating (for more details, see Sections 7.2.2 and 11.3.3).

The underground mining industry faces challenges associated with ventilation of diesel mobile equipment. Depending on specifics of a mine, BEVs offer many benefits:

- Potential to significantly reduce air volumes compared to those required from the use of diesel equipment fleets
- Potential to reduce refrigeration loads associated with a reduced ventilation in deep hot mines
- Improved working environment in mine headings with low to no diesel particulate and combustion gas emissions and reduced noise levels
- Greenhouse gas emissions and operating costs are further lowered
- If mines have ventilation-constrained areas, there is potential to increase production with simultaneous BEV usage
- BEVs have strong low-speed torque that is favourable to operators

However, BEVs also present new challenges for mine operators in terms of infrastructure requirements and maintenance and operating constraints. Charging infrastructure will become a key requirement for a mine. One intent of this document is to provide guidance and act as a discussion document regarding required charging infrastructure. Within this guideline, lithium ion batteries (LIBs) are the reference technology for BEVs in mines.

5.1 Advantages of BEVs versus Traditional Diesel Equipment

The benefits of employing BEVs are arguably greater for mining than any other industry. The noise, heat, and odour generated from diesel engines negatively affect the underground work environment. Diesel emissions (carbon monoxide and dioxide, nitrogen and sulfur oxides, hydrocarbons, and particulates) pose a health hazard and have recently been classified as “Group 1: carcinogenic to humans” by the World Health Organization (International Agency for Research on Cancer, 2012). At the same time, the American Conference of Governmental Industrial Hygienists (2012) has reduced the NO_2 threshold limit value from diesel engines from 3 to 0.2 mL/m^3. Protecting workers underground from diesel emissions requires expensive (capital, operating, and maintenance costs) and electricity-consuming ventilation and cooling infrastructure, and other measures, such as diesel particulate filters and diesel oxidization catalysts (e.g., Stachulak, Allen, & Hensel, 2015; Stachulak, Gangal, & Allen, 2016).

Relative to diesel-powered vehicles, BEVs are quiet, more responsive, have fewer moving parts, require less maintenance, and emit fewer greenhouse gas and other gaseous and liquid (e.g., oil, transmission and radiator fluid) pollutants, and less diesel particulate matter. Thus, the work environment is cleaner, even in haulage routes. Several technical papers have been published describing the efficiency benefits of battery electric drives over internal combustion engines. Depending on the specific application, the portion of energy transferred to the wheels can be as much as 5 times greater (Center for Energy, Transportation and the Environment, 2017). Further, BEVs are broadly perceived as socially acceptable (Hanke, Hülsmann, & Fornahl, 2014). Unlike a diesel vehicle, when the BEV is parked the engine is not idling; therefore energy consumption and heat output are lower. BEVs currently may be the preferred choice for mines that must exploit deeper resources, where cooling (virgin rock temperatures can reach 80°C; Fiscor, 2014) and ventilation costs would otherwise make the project unfeasible.

5.2 Disadvantages of BEVs versus Traditional Diesel Equipment

High energy content is the largest benefit of fossil fuels. The gravimetric energy density (specific energy or energy per unit mass) refers to the capacity to store energy, thus it determines a vehicle’s range. The energy density of diesel is nearly 50 MJ/kg—more than 80 times higher than the most energy-dense LIB (0.61 MJ/kg; Thackeray, Wolverton, & Isaacs, 2012; Recharge, 2013). The volumetric energy density of diesel is approximately 35 MJ/L—14 times higher than the most energy-dense LIB (2. MJ/L). New anode and cathode materials could double the energy of density of LIBs, but other avenues need to be explored to improve battery performance (Thackeray et al., 2012).

The higher energy content of diesel is somewhat offset by low efficiency of use: a significant portion of the energy content is lost in the form of heat when diesel is combusted. By comparison, the loss of energy to heat by LIBs via activation, concentration, and ohmic losses is negligible (Chen, Cong, Yang, Tan, Li, & Ding, 2009; Bandhauer, Garimella, & Fuller, 2011). In addition, BEVs are able to implement regenerative braking, electric engines don't idle at rest, and they lack losses associated with mechanical components such as torque converters. Despite these compensations, the net energy content is still substantially higher in diesel than LIBs.

Standardized fuel is a key advantage of diesel-based equipment. Refineries handle the complexities of converting raw petroleum products into a portable fuel. Thus, refueling is the simple act of pouring liquid into a vehicle fuel tank. BEVs do not share this convenience: the battery pack is a more complex energy storage medium and the battery recharging process is significantly more complicated. In addition, the BEV market is still in its infancy: methods to deliver a charge are not standardized across the industry.

6. CHARGING PHILOSOPHY: THE FOUNDATION OF PLANNING AN ELECTRIC MINE

A successful electric mine design begins with understanding and harnessing the benefits of BEVs, while accounting for the shortcomings outlined above. In a mine with diesel-based mobile equipment, thought is seldom given to the parking arrangement for vehicles, and minimal planning is needed to provide for diesel fuel distribution. In contrast, in a mine based around BEVs, these considerations are crucial to success. Without careful design, it would be very easy to end up with an array of incompatible charging stations throughout the mine. The ultimate objective is to make recharging and operating BEVs as simple, convenient, and safe as refuelling and operating diesel vehicles.

A BEV charging system typically consists of a step-down and isolation transformer, a rectification system / variable DC supply, and a charge rate controller. The four basic approaches to designing a charging system are described below in terms of the charging philosophy: how it affects decisions regarding mine design, BEV design, the charging system, and performance requirement evaluation.

6.1 On-Board Charging from Alternating Current (AC) Supply

With an on-board charging from AC supply arrangement, the connection to the BEV is via an AC plug (Figure 1). Equipment for converting AC to direct current (DC) is located on board the BEV and consists minimally of power electronics for rectification and regulation. In addition, a transformer may be required to step the voltage up or down and provide some isolation from the fixed power system.

6.1.1 Design Considerations The mine design must include AC connections where BEVs will be parked, similar to what is traditionally done with diesel vehicles. The BEV design requires an integrated charger on the BEV, with the plug type chosen that is specific to the mine / jurisdiction. The charging system is not a consideration because the charger is on the BEV. All of the responsibility for performance is in the hands of the BEV OEM.

When first considering BEVs in a mine, the most obvious approach is to adapt the mobile equipment connectors currently used for drills and bolters in diesel-based mines to charging BEVs. This seems to be a straightforward strategy: it requires very little fixed infrastructure, the BEV OEM would supply everything on the BEV (including an on-board charger), and to charge the equipment, it would simply be a case of connecting the charger to the AC supply. In addition to the AC supply, a pilot circuit should be considered when the charging power increases. Given that it is hard to tell when charging is occurring, there is a risk of arcing if the plug is disconnected during a high power charge. Live parts of the connector should also be protected with an automatic shutoff or appropriate ingress protection to prevent undesired contact. Although on-board charging for the entire fleet appears to be the most convenient and simple option, on-board charging BEV and drivetrain OEMs have identified several concerns (Section 6.1.4).

6.1.2 Charging Interface A connector carrying AC is brought to the BEV. Because the power conversion equipment is on board the BEV, most communication needed to regulate charge rates also takes place on board the BEV. This minimizes the amount of communication needed through the connector between the mobile and stationary equipment.

For commercial BEVs, on-board charging is generally used for low-rate charging (e.g., at the owner's home or business). Connector types are defined by IEC 62196-1:2014, IEC 62196-2:2016, and IEC 62196-3:2014 and vary depending on locale (International Electrotechnical Com-

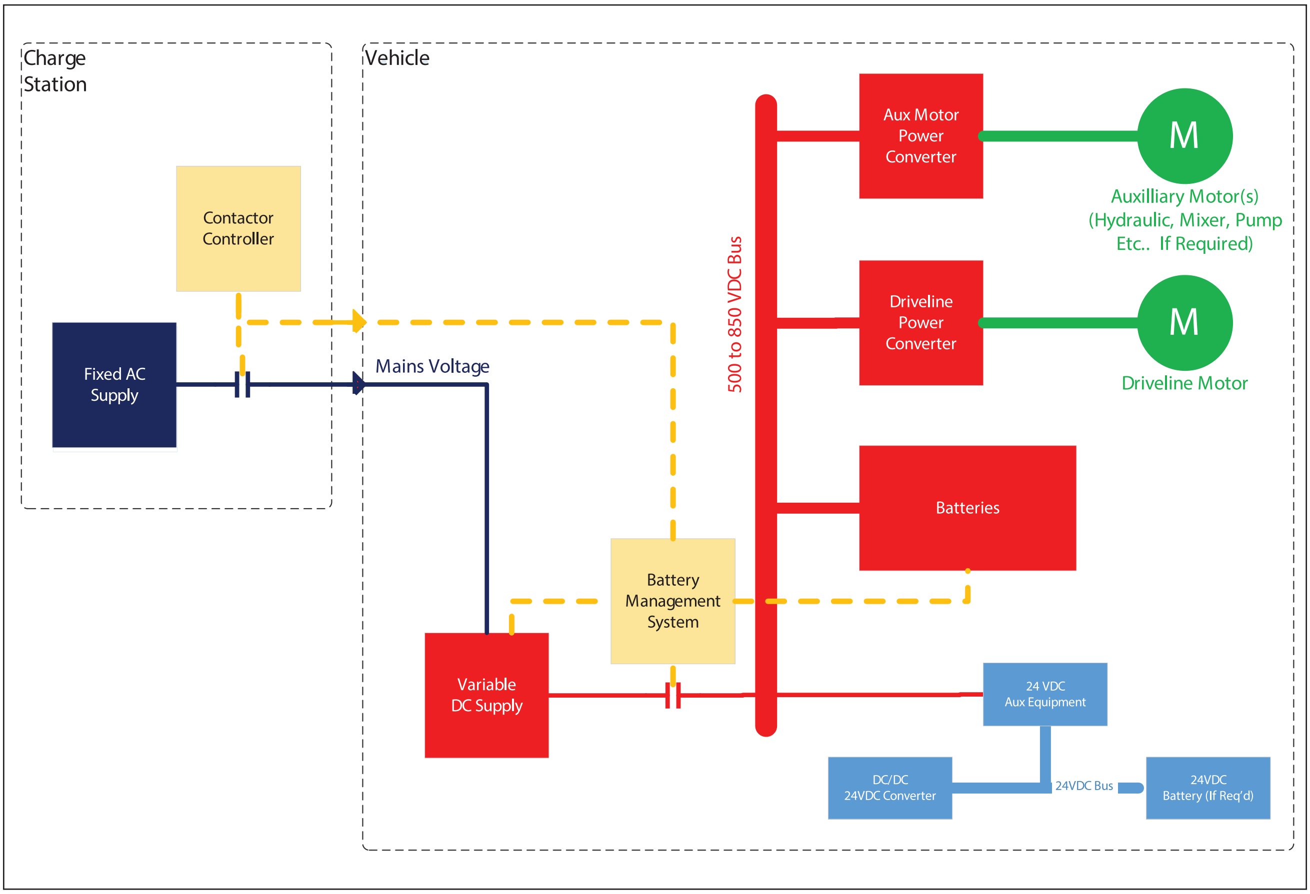


Figure 1. Typical On-Board Charging Arrangement (VDC: Volts Direct Current)

mission, 2014a, b, 2016a). For North America, BEVs have standardized on the IEC 62196 Type 1 (SAE J1772) connector (SAE International, 2016; Figure 2). The three pin sizes are, from largest to smallest, AC line 1 and line 2, a ground pin, proximity detection, and control pilot. The connector is capable of delivering 80 A at 240 volts AC (VAC; 1 Phase), which provides up to 19.2 kW of power. In Europe, a higher capacity Type 2 connector (VDE-AR-E 2623-2-2) is employed, supporting a higher voltage but lower current, delivering up to 22 kW.

Figure 2. SAE J1772 Connector (Hicks, 2012)

The signalling over the IEC 62196 connectors for AC charging is limited to:

1. Determining whether the plug is inserted into the BEV
2. Indicating to the BEV the available mains current, so the BEV does not attempt to draw more current than the charging station is able to deliver

6.1.3 Advantages

1. The charger is carried with the BEV, eliminating the need to install a separate enclosure within the mine to house the charger.
2. The charging location is more flexible. A dedicated charging unit in a particular location is not needed to execute a charge.
3. OEMs are free to optimize the charger and battery arrangement to suit the BEV.

4. Handshaking and communications between the BEV and the stationary connection are minimized or eliminated.

6.1.4 Disadvantages

1. It is difficult for BEV OEMs to accommodate batteries and drivetrain equipment on large equipment such as load haul dump (LHD) machines and haulage trucks. A large capacity, on-board charger—including power electronics (and sometimes a transformer)—only adds to this challenge. Ergonomics and operator visibility are often compromised.
2. The added weight and volume of the on-board charger consumes space and can limit the range of the BEV.
3. The charging equipment remains with the BEV, where it is exposed to dust, temperature extremes, vibrations, and other harsh operational conditions.
4. With high-capacity chargers, the power electronics must be cooled while the charge is underway.
5. Each BEV would likely have a customized charger, increasing the spare parts inventory, maintenance requirements, and repair difficulty.
6. Practical limitations exist on how powerful an on-board charger can be. The more advanced commercial BEV industry has taken an off-board approach for high-capacity charging.

These issues can probably be resolved when considering a small, low-rate charger (< 20 kW). However, many issues could become prohibitive as the capacity of the charger increases. Even in cases where issues can be resolved, costs tend to increase because each BEV needs to be equipped with a charger. Further, design difficulties increase because OEM engineers must balance battery size, charger size, and charge equipment cooling and protection—all while trying to find space for the charger on the various mobile platforms.

Whereas OEMs for smaller utility type BEVs are able to accommodate a request for on-board charging, experience to date has shown that OEMs for large trucks and LHD machines are either reluctant or unable to do so. At the time of writing, it seems unlikely that on-board charging across an entire fleet will be a reality.

6.2 Off-Board Charging of On-Board Batteries

The off-board charging arrangement locates the transformers and rectification equipment in a fixed enclosure removed from the BEV (Figure 3).

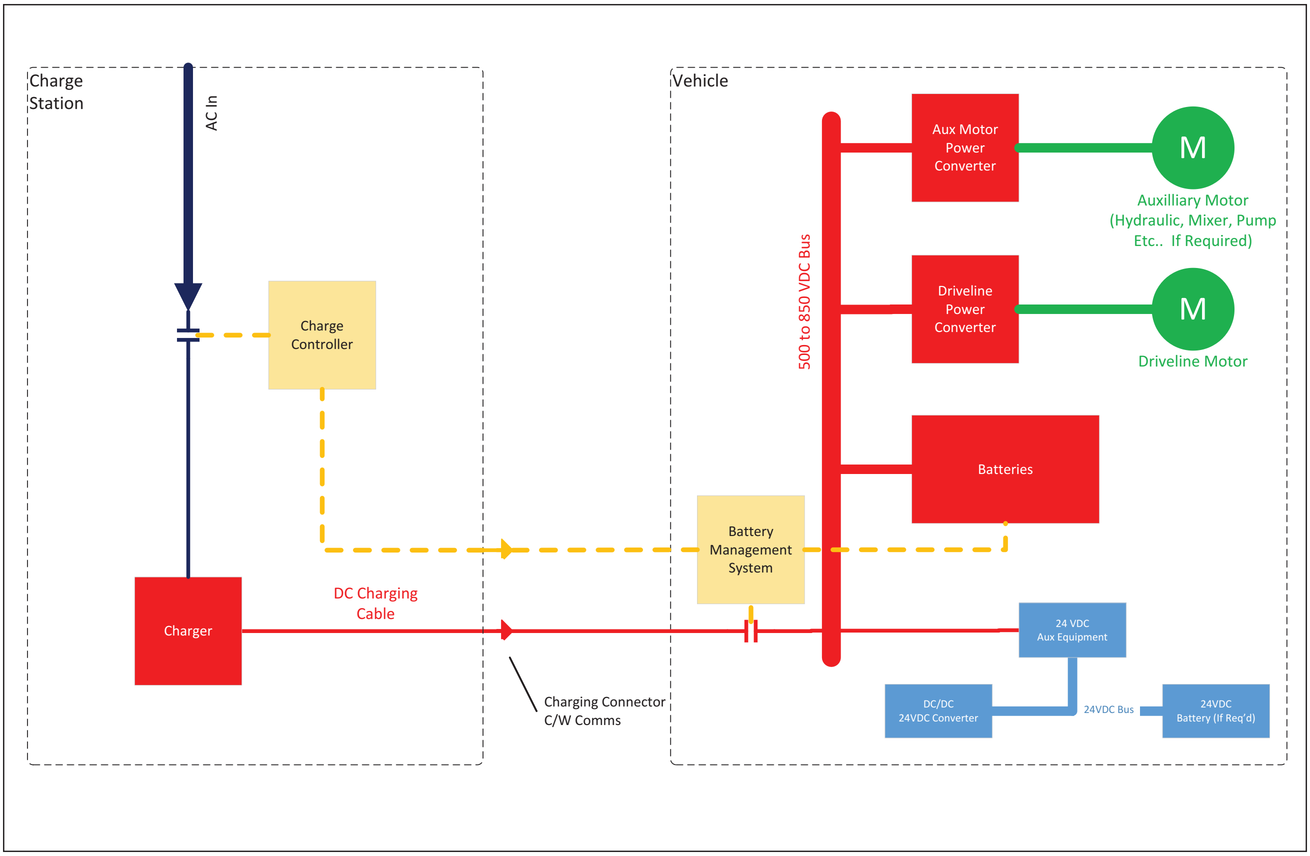


Figure 3. Off-Board Charging Arrangement (VDC: Volts Direct Current)

6.2.1 Design Considerations The mine design must include charging stations where BEVs will be parked. The BEV design must specify the charger protocol / plug type (Section 6.2.2.1). The charging system design must meet specific protocol / plug type, or be proprietary and supplied by BEV OEM.

6.2.2 Charging Interface

6.2.2.1 Cable The power electronics for converting the AC line voltage to DC for charging is housed within stationary equipment next to the BEV. Hence, a DC connector is used. While the charge is taking place, the BEV battery management system (BMS) needs to constantly vary the current delivered. The BMS monitors the energy consumed by the BEV while being driven, as well as temperature, individual cell voltages, and total pack voltage. During charging, the same process is monitored in reverse, creating a safety net in the event of problems with a single cell within the battery pack. Typically, up to approximately 80% state of charge (SOC), the BEV will demand relatively high amounts of power. Demand will taper off as the charge progresses into the final phases to prevent damage to battery packs. Since the BEV is requesting the changes in charge rate and the charger is varying the rate, a robust means of communicating between the two units is essential. This contrasts with on-board charging, where communication over the connector is limited to initial handshaking.

Standardization of cable connectors has not yet taken place with commercial BEVs. At least four connector types are in use.

1. More than 10,000 CHAdeMO connectors have been installed to date worldwide (Figure 4). This connector has found widespread acceptance in Japan (i.e., automakers Nissan, Mitsubishi, Toyota, and Subaru), along the west coast of North America, and in some parts of Europe. Chargers are currently limited to 62.5 kW (125 A at 500 VDC), though the connector is rated for up to 100 kW (200 A at 500 VDC).
2. American and European—in particular all German—automakers favour the existing Type 1 and Type 2 connectors (Section 6.1.2), with two DC pins added (CCS; Figure 5). The SAE J1772-based connector (SAE International, 2016) is rated for 120 kW (200 A at 600 VDC), while the VDE type is suitable for up to 170 kW (200 A at 850 VDC). Chargers manufactured to date appear to be limited to approximately 50 kW.
3. China has implemented a separate GB/T type connector, capable of 187.5 kW (250 A at 750 VDC; Figure 5).

Tesla Motors has developed a proprietary “supercharger” system that is exclusive to their vehicle line; they are installing a network of such charging stations throughout North America, capable of delivering up to 120 kW.

To date, there is little sign the automotive industry is converging on one standard charger. Thus, OEMs have responded by accommodating multiple standards on a single charger. Major OEMs such as ABB, Siemens, Schneider, and GE have DC chargers on the market today with a typical capacity of 50 kW. For example, ABB offers a 50 kW charger that supports both CHAdeMO and CCS (Figure 6a). The higher capacity charger manufactured by EVTEC (Figure 6b) supports both AC (Type 2) and DC (CHAdeMO + CCS) charging, and is capable of connecting to multiple BEVs simultaneously, splitting the charge capacity among them.

6.2.2.2 Pantograph As an alternative to connector-based charging, pantograph-based systems are being used to

Figure 4. CHAdeMO Connector (Kane, 2013)

Figure 5. CCS and GB/T Type Connectors (Phoenix Contact, 2017)

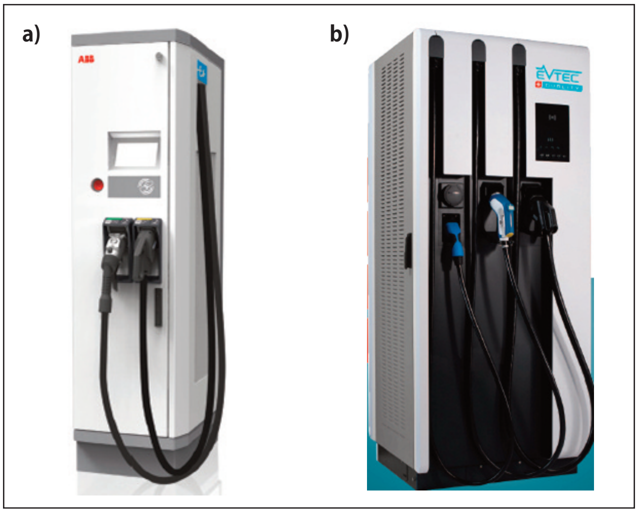


Figure 6. a) Typical 50 kW Charger Manufactured by ABB (ABB, 2017) and b) Higher Capacity Charger Manufactured by EVTEC (EVTEC, 2017)

charge larger BEVs such as city buses (Figure 7). Pantographs are mechanical linkages connected such that the movement of one arm produces identical movements in a second arm. Pantograph charging is not yet standardized. Some varieties are mounted on board the BEV and extend upwards to make contact with the charger. In others, the pantograph is mounted on the infrastructure and extends downward onto charging rails on the roof of the BEV. In the charging station, communication is established between the BEV and the charger. An overhead connection is lowered onto the BEV via a pantograph, mating with the charging rails. After completing a safety check, the charge is initiated. In general, the charge rate of the pantograph arrangement is high (150–450 kW).

6.2.3 Off-Board Proprietary Chargers If on-board charging is not feasible, the OEM could develop and supply an off-board charger for the BEV. This approach is very simple from an engineering and commercial standpoint—the charger is specifically designed for the BEV, ordered, and delivered with the BEV. However, with 80–100 BEVs in the fleet throughout the mine, a specific charger for every type of BEV is cumbersome. Each piece of equipment would need to be assessed, potential charging locations determined, and an equipment-specific charger installed. The result would likely be multiple charger types at each location. In addition, personnel would need to be trained on the various charging interfaces and support personnel would need to be capable of troubleshooting them. Ultimately, a mess of incompatible charging systems would be scattered throughout the mine.

Figure 7. Pantograph Overhead E-Bus Charger (Siemens, 2017)

One possible remedy to these concerns is to use one OEM for the BEV drivetrain to standardize the entire mine. Experience has shown that dictating to OEMs the type of equipment and technology to use on board their BEVs stifles innovation, leads to complications, and yields a poorer product. This approach also increases risk because the mine completely depends on a single vendor.

Proprietary charging solutions may be a reasonable option for a few initial "trial" BEVs, or in a small-scale deployment of a handful of BEVs. However, they may be infeasible for full-scale deployment of BEVs throughout a mine.

6.2.4 Off-Board Standardized Charging Interface As with the commercial BEV industry, the solution for mining BEVs may be to standardize the charging interface. Once the connector, voltage range, and communications between the charger and BEV are agreed upon, a BEV from one OEM could be connected to a charger from another OEM. An obvious consideration is to adopt a standard from the commercial BEV industry. However, the demands of a mining BEV differ from those of a passenger BEV. The entire charging arrangement needs to be rugged to withstand the harsh mining environment. The connectors, charger, voltages, charge rates, and communication methods need to be suitable for a mining BEV drivetrain and battery. If these issues can be addressed, then the mining industry would benefit from the research and development already invested by the commercial BEV industry. If not, then the development of a "mining only" interface may be the only solution. However, achieving agreement on connector type, communication protocol, handshaking, and other details will be challenging.

6.2.5 Advantages

1. BEV size and weight are low because charging equipment is not on the BEV.

2. If practical, chargers can be located in cool and contaminant-free areas.
3. High-capacity chargers are feasible because size and weight are not issues.
4. Multiple BEVs can share one charger if connectors and communication protocols are compatible between BEVs.
5. Off-board charging is the charger standard in parallel industries such as public transport and port equipment.
6. For proprietary charging interfaces, the responsibility for the entire system (i.e., drivetrain, batteries, and charger) lies with the OEM.
7. BEV OEMs can focus on building high-quality mining BEVs, rather than developing or supplying chargers. Similarly, electrical equipment suppliers can develop rugged BEV chargers, without entering the BEV business. It is feasible for an OEM to build both chargers and BEV drivetrains, as long as the charging interface is standardized.
8. Those in charge of procuring mobile equipment are free to purchase any type of BEV from any OEM.
9. The fixed plant department are free to purchase and install charging infrastructure regardless of the BEV OEM.
10. For equipment operators (instructed persons defined in International Electrotechnical Commission, 2004), a simple and consistent charging interface across the mine eliminates confusion and additional training. The type of BEV or location within the mine is irrelevant—simply plug in the BEV and initiate the charge.
11. From a risk perspective, the worry that “all eggs are in one basket” is greatly diminished. If one OEM has a technical issue, only one relationship is affected. If an OEM goes out of business, the mine does not have an entire fleet of unsupported equipment and infrastructure.

6.2.6 Disadvantages

1. Space must be allocated in the mine to house charging equipment.
2. The BEV must move to a specific location to charge.
3. Greater potential exists for a variety of chargers, leading to handshaking and communication problems between the charger and BEV.
4. Pantograph-based systems are delicate and prone to malfunction.

6.3 Off-Board Charging of Off-Board Batteries (“Swapping”)

The charging strategies above involve charging a battery mounted on the BEV. With battery swapping, a discharged battery is removed from the BEV and

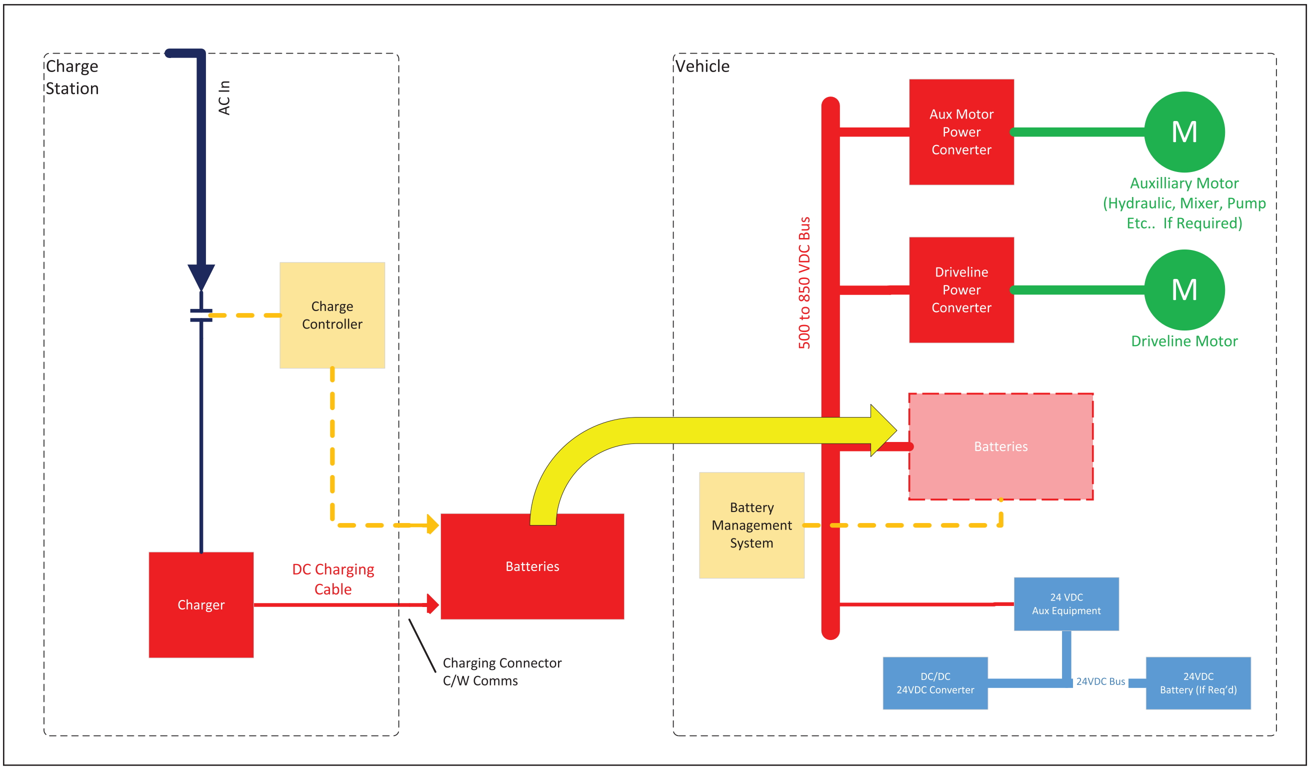


Figure 8. Battery Swapping Arrangement (VDC: Volts Direct Current)

replaced with a fully charged one (Figure 8). The BEV can resume work while the depleted battery is charged. Battery swapping is a viable option that is already used in mining. The energy density limitations of LIBs (Section 5.2) mean swapping may be the only option if long uphill trips are unavoidable, especially if implementing BEVs in existing mines.

6.3.1 Design Considerations

The mine design would not require designated parking for each BEV, but would require swap-and-charge stations. Some fixed charging infrastructure could be eliminated in favour of a swap-and-charge station. The BEV design must include the ability to swap batteries easily (accessible) and safely. The charging system would be designed into the charging station.

6.3.2 Charging Interface

The interface for a battery swapping arrangement will be proprietary to the BEV or battery OEM. Typically, the battery is disconnected from the BEV, then removed via a crane, forklift, or on-board lifting mechanism. In many cases, the battery can be left on board the BEV while charging, but this inhibits the use of the BEV during charging. Once the battery has been disconnected from the BEV, it is directly connected to the charger. Upon completion of the charge, the reverse process is followed to reinstall and reconnect the battery on board the BEV.

6.3.3 Advantages

1. BEVs can undergo multiple battery swaps in a production shift, which could permit a smaller on-board battery capacity. The battery could be sized to last for short periods and the mining schedule arranged so swap-outs occur at predetermined intervals.
2. This option enables long uphill haulage.
3. Some charging infrastructure can be eliminated in favour of a swap-out station.
4. Designated parking for each BEV would not be required.
5. BEVs do not need to be plugged in at the end of a shift.

6.3.4 Disadvantages

1. Complications are involved in removing the batteries.
    a. A manual arrangement (e.g., crane) presents both logistic and safety concerns, given the high frequency of swap-outs.
    b. An automated arrangement would suffer from wear and tear in the mining environment, and would require a high level of engineering effort to accommodate all types of BEV.
    c. BEV design options could be limited by the need to facilitate battery removal.
2. Fixed infrastructure is required.
    a. Dedicated swap-and-charge stations would be needed in strategic locations throughout the mine.
    b. The swap-and-charge infrastructure would likely be large, translating into significantly more mining excavation to house the equipment.
    c. The swap-and-charge stations would be complicated: failure of one station could be a point of failure for the entire BEV mining fleet.
    d. Limited battery charging locations means much of the mining fleet would need to leave their work areas to pass through the swap-and-charge stations.
3. Battery inventory management is challenging.
    a. A substantial battery inventory would be required (e.g., three batteries for every two BEVs), mitigated by the fact that the batteries could be lower capacity.
    b. It is unrealistic to have a standardized battery type deployed across the entire fleet if more than one OEM is used, resulting in management difficulties.

A battery swap strategy has many challenges. With changes to mine layout, it may be possible to eliminate the need to swap batteries, or at least limit swapping to a handful of BEVs. In general, an on-board strategy should be pursued wherever possible, with swapping considered only if other alternatives prove infeasible.

6.4 Hybrid Charging Method

A combination of on- and off-board charging arrangements can offer some benefits of both (Figure 9). The on-board component is a low-capacity charger that allows the batteries to be recharged over a relatively long time span. If a fast charge is required, the BEV is driven to an off-board rapid charger. Proper isolation must be designed to avoid interaction between the operator and electrical energy.

Most commercial BEVs employ a hybrid arrangement. Typical commuter, home- or business-based charging stations supply AC power to the BEV, which then uses an on-board charger to convert to DC and regulate the charge rate. For a long-distance trip beyond the capacity of a single battery charge, the driver pulls into a dedicated off-board facility with higher rate charging.

6.5 Establishing the Charging Philosophy

When designing a BEV-based mine, a key to success is to establish the battery charging philosophy. The choice of charging arrangement from among the four approaches above must be tailored to a given mine based upon many factors, including:

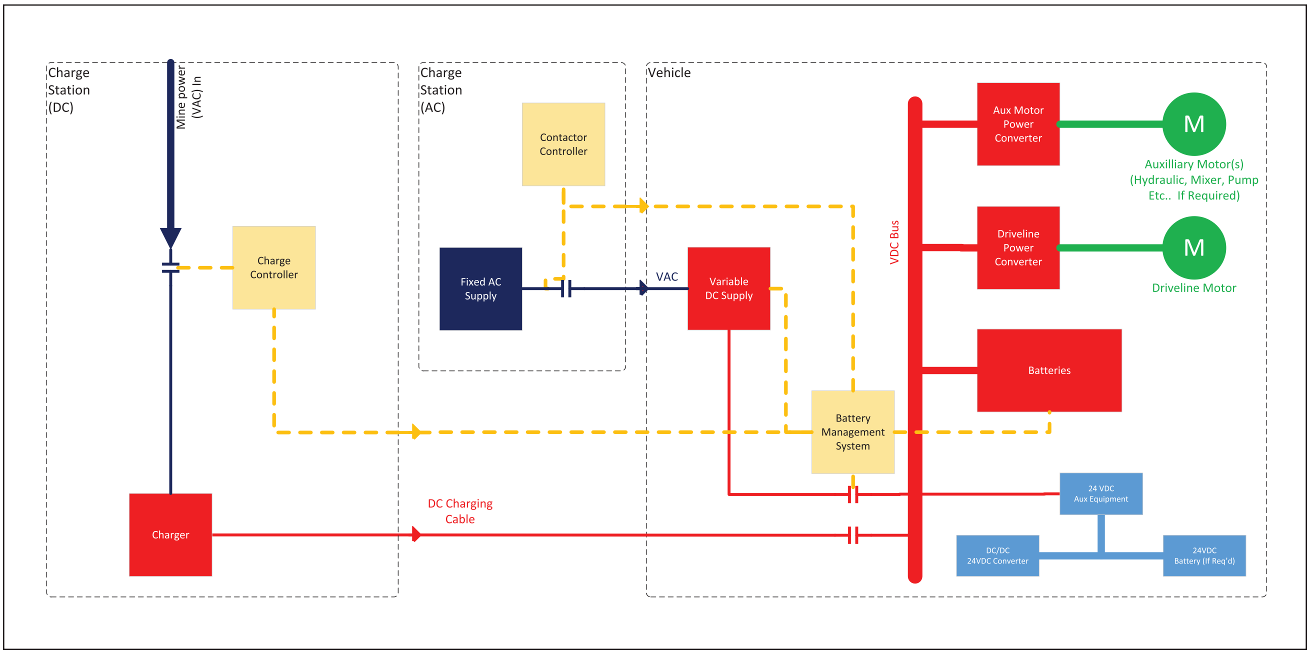


Figure 9. Typical Hybrid Charging Arrangement

- Whether the mine will be fully electric, or some diesel vehicles will be employed
- Greenfield development or brownfield mine
- Size and capacity of vehicles and/or mine workings
- Available battery capacity for given vehicle class
- Haulage routing: uphill, downhill or at grade
- Available and desired ventilation
- Shift schedule relative to when charging will take place

The decision to deploy mining BEVs will also affect many of the factors above. For example, an existing mine with ramp access to depth may be forced to employ some diesel haulage vehicles because a large BEV battery would prohibit uphill haulage. By contrast, a greenfield mine may choose to sink a deeper shaft to enable downhill haulage, thus taking advantage of BEV regenerative braking (Sections 7.2.2 and 11.3.3).

Considerations for charging philosophy include any of the following:

1. Standardize—to the extent possible—the entire mine with one type of charger.
    a. If only smaller BEVs will be deployed and/or if charge time is not a significant concern, on-board charging may be the easiest option.
    b. If one OEM will supply all (or most) of the BEVs, a proprietary off-board charger developed by that OEM may be appropriate.
    c. If multiple OEMs will be supplying BEVs, a standard charging protocol such as CCS Type 2 (see Section 6.2.2.1) may be appropriate. In this case, the mine must specify the charge port type on all BEVs to be procured.
2. Consider hybrid charging (Section 6.4) for BEVs equipped with a trailing cable (e.g., drills, bolters, loaders). These can be equipped with both a DC "fast charge" port and a small on-board charger to permit slower charging while operating.
3. Carefully plan the parking arrangement, with a designated parking spot for each BEV (Section 7.2.3).
4. For substantial deployment of BEVs of all sizes, consider equipping the mine with two capacities of standardized off-board charger with universal charge interfaces.
    a. For large BEVs (LHD machines and haulage trucks), install high-capacity chargers. These should be as powerful as possible (e.g., 200 kW or higher).
    b. For small BEVs (man carriers, utility vehicles), chargers in the 20–50 kW range are sufficient.
    c. If a large BEV is connected to a low-power charger, the charge proceeds but takes longer.
    d. If a small BEV is connected to a high-power charger, the charger limits output power to what the BEV is able to accept.
5. For many locations in the mine, very long charging cables (> 200 m between charger and BEV) may be beneficial.
6. If long uphill haulage is required, a battery swapping arrangement may be considered. This requires some infrastructure for battery removal, and likely involves co-operation with a BEV OEM.

7. Chargers should have a wide output voltage range (e.g., 300–850 VDC).

7. MINE DESIGN

7.1 Introduction

Mine design considerations will adjust to accommodate mine electrification. The primary drivers for this change are lower requirements than diesel to ventilate emissions and heat and expected reduction in the size and quantity of ventilation shafts and drifts. Health and logistical benefits from eliminating diesel fuel are also attractive.

Whether the application is for a greenfield or brownfield site, performance parameters of each piece of equipment require consideration as changes to fleet and mining methods are defined (Section 11). When designing a layout for an all-electric (battery and/or tethered) or hybrid mine (mixture of diesel and BEVs), additional infrastructure will be required throughout the mine to maintain and operate the BEV fleet. The first considerations relate to charging method:

- Charging philosophy (Section 6): on-board or off-board charging or battery swapping
    - Each approach requires different infrastructure (e.g., excavations and electrical systems)
- Mining cycle and schedules for charge time vs. operating time
- Power regeneration opportunities
- Cost implications of charging methods

Depending on the charging method chosen, additional infrastructure design options include:

- Charging stations at dedicated locations
    - Shared chargers
    - One size fits all
    - Specific chargers match specific equipment
    - Footprint
        - Charger
        - Sufficient room to park a BEV and leave it aside to charge
        - Sufficient power source for the charger
- Battery maintenance shop / facilities / equipment
    - Effective communications from underground to OEM
    - Dedicated maintenance battery charger(s)
    - Spare batteries and chargers
- Swap-out station(s) if battery swapping will occur during shifts
    - Significant excavations that require special attention
    - Anticipated procedures for swapping batteries
    - Adequate rigging and lifting capabilities
- Mechanical / electrical garage
    - If the mine is all-electric, the layout needs to be reconfigured, since diesel engine maintenance and repairs will no longer be required. A garage is still required for:
        - Rebuilding scoop buckets
        - Tire changes
        - Drive train work (if applicable)
        - Hydraulic system maintenance
        - Electric maintenance (motor, battery, computer, and charger)
        - Additional service on secondary equipment
    - BEVs have few moving parts, thus require less equipment in a warehouse / spare parts location
        - Minimum spare parts should be reviewed with OEM to ensure sufficient real-estate is reserved
    - BEVs have specific requirements for spare parts and for workers with the appropriate skillsets (Table 1)

Once the electric mine is operating, numerical data should be collected and analyzed to better define and support the many advantages associated with a BEV fleet (Section 5.1).

7.2 Mine Layout and Infrastructure

Mining companies and engineering firms are accustomed to developing the layout and infrastructure of a mine to accommodate diesel mobile equipment. In transitioning to mining BEVs, it is essential to reconsider the traditional methods of mine development.

There are many advantages to transitioning to mining BEVs such as less need for ventilation, lower energy cost, less heat and noise, and improved working conditions. Nonetheless, BEVs have several limitations relative to traditional diesel equipment, the most important being the limited range and time needed to charge. The key to a

Table 1. Training requirements

Role	Training Level
Instructed person	Operator with minimal training for battery user interface and charging (International Electrotechnical Commission, 2004)
Mechanic	Required for non-electric components (e.g., hydraulic packs)
Electrician	Possibly with aptitude for instrumentation; likely require additional personnel specifically trained for battery electric equipment (similar to instrumentation technologists)
Remote service / support	Additional skillsets may be required when troubleshooting—perhaps direct toward OEMs and/or engineers
Fuel / charging	All workers need to be trained to conduct the chosen charging method

successful BEV-based mining development will be ensuring the mine is well planned and equipped to accommodate the BEVs, while fully harnessing the benefits that come with the technology.

The sections below provide a brief discussion around some of the major areas to be considered when tailoring a mine for BEVs.

7.2.1 Ore / Waste Handling System (OWHS) The OWHS consumes large amounts of energy (diesel, electrical, or battery). Therefore, it requires the most consideration because it places the highest demand on electric equipment. During OWHS design, various trade-offs will likely occur before use of electric equipment is confirmed. Whereas ventilation / cooling systems will benefit the most (e.g., air quality, humidity, noise, and maintenance) by the implementation of an electric fleet, the OWHS has the greatest chance of being affected. Thus, this section focuses on the impact of electrification, not OWHS design or current methods such as diesel equipment, conveyors, or train cars. Understanding BEV operation is crucial to optimizing the OWHS capability.

With the advent of BEVs, new optimization methods are sure to follow. For example, if it is possible to haul ore downhill, regenerative braking (Sections 7.2.2 and 11.3.3) can optimize the use of gravity to capture some of the kinetic energy as follows—depending on OEM, grade, site conditions, and other factors:

1. BEV leaves a charging station fully charged (X%) at the start of shift
2. BEV travels up to the mining face and is loaded with ore (discharged to X%–losses)
3. BEV travels down ramp to destination prior to entering the loading pocket (based on the elevation in the mine, the BMS determines the ratio of regenerative and actual braking to use to recharge to some level less than X%)
4. Cycle is repeated until charging is required

Regeneration of energy should be simulated to match the equipment performance to specific applications.

If downhill ore / waste movement is not feasible, mining methods could be selected to minimize the withdrawal of ore at elevations lower than the OWHS destination. Top-down mining methods or electric / battery haulage to a centralized point with a conveyor uphill are options to reduce the uphill travel of ore in terms of tonnes and distance. With BEV use, ore passes may no longer be the preferred method of moving ore. Figure 10 shows the OWHS options that affect the battery size and energy requirements of a BEV. Ultimately, the haulage system design will influence the duty cycle (i.e., the time taken by the cycle of operation relative to the available time) required from the battery and charging system (Sections 7.4.1 and 11.2.1).

7.2.1.1 Trolley assist systems Trolley assist systems collect electricity from overhead conductors for use by electric motors. An example is the Kiruna truck system from Sweden that has been in use for decades, but adoption is limited by:

- High capital and maintenance costs
- Tight tolerance roadbeds
- Tight constraints of the overhead electric conductor system
- The need to keep roadbeds cleared to maintain contact with the overhead power bar

Kiruna trucks are currently fitted with small diesel engines that allow for short horizontal movements while disconnected from the trolley. There could be potential to design a hybrid Kiruna-style truck with battery-powered motors that would allow longer trams while disconnected (e.g., the Scania etruck system). With the move toward electrification of the mining fleet, the recharging opportunity in ramps or drifts using an overhead power bar system becomes more attractive. Further work is required by industry and vendors to develop trolley assist systems applicable

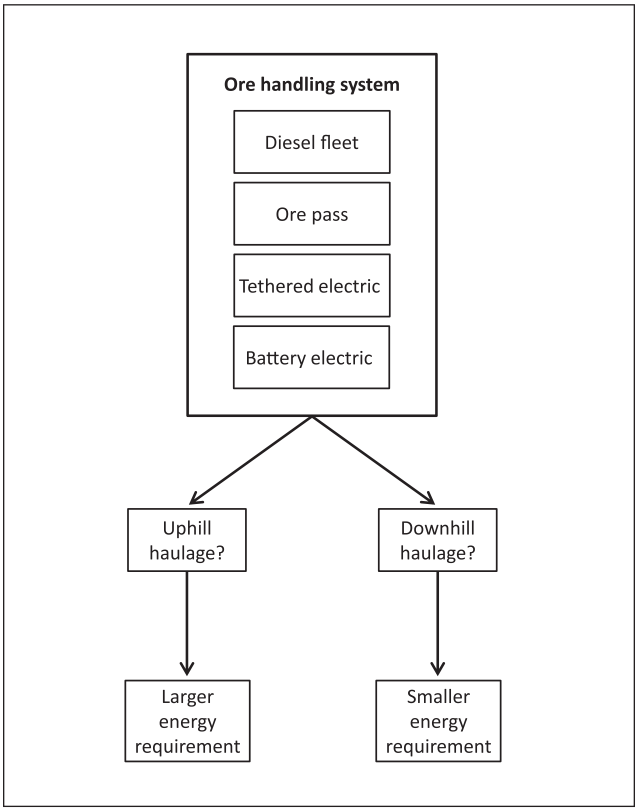


Figure 10. Impact of Ore / Waste Handling System on Battery Sizing

to mines that address the adoption challenges noted above. Open pit mining, urban transit, and recent highway trials in Sweden can be referenced for mine design.

7.2.2 Regenerative Braking Compared to diesel, the energy density of batteries is by far the greatest limitation to be overcome for BEV adoption (Section 5.2). However, the regenerative capabilities of electric motors can potentially lessen the magnitude of this problem (Section 11.3.3). With a diesel vehicle, braking converts kinetic energy into heat. When braking a BEV, the motors push most of the kinetic energy into the on-board batteries. This has the following advantages:

1. Longer BEV range
2. Lower energy consumption (higher efficiency)
3. Batteries may be sized smaller
4. Unlike friction braking, which converts all the energy to heat, regenerative braking converts some energy to electricity, producing less heat in the mine environment

It is important to lay out the mine to maximize the benefits of regenerative braking. Ore / waste haulage is one area where careful planning can pay big dividends (Section 7.2.1). An electric truck that hauls material primarily uphill and returns empty downhill will require very large batteries, and is not likely to last an entire shift (Figure 10). Reversing this pattern—hauling the material downhill—can drastically improve the range. In some cases, it may be possible to run for several shifts without needing to charge the battery. This strategy takes advantage of the gravitational energy contained within the ore and waste, and using it to recharge the batteries on board the BEV.

Regenerative braking can be a double-edged sword. A fully charged BEV that needs to make a long downhill journey may not be able to store the braking energy, and would rely on friction braking or braking resistors. It is best to avoid this situation altogether through careful planning, for example by positioning charging locations at the bottom of a ramp, or limiting the amount of charge taken on if a downhill trip is anticipated.

7.2.3 Vehicle Parking When planning a mine development, engineering firms generally do not emphasize establishing parking locations for all the vehicles in the fleet. With diesel equipment, this approach is generally acceptable since empty cutouts or old stope accesses / drawpoints can generally be relied upon to provide suitable parking locations. The most significant problems might be logistical issues or conflicts among crews over vehicle parking.

With a BEV-based mine, it is essential that a parking and charging strategy is carefully laid out. If a BEV is parked in an arbitrary location, it cannot be charged and will likely be unavailable for the next shift. It will also be important to change the culture of the workforce to suit a BEV fleet. At the end of every shift, it will be essential for every operator to park their BEV in its designated location and connect it to a charger.

Effective BEV and charger status updates will be essential. The mine monitoring system should track the status of every BEV during and at the end of the shift. This will allow effective planning by giving advance notice as to the state of the fleet, thereby reducing the chance of arriving at a BEV to discover it is not charged and ready to use.

7.3 Personnel Movement

Standard methods for personnel transport from surface to various mine locations are via a service cage for shaft access mines, a vehicle for ramp access mines, or a combination of both methods.

7.3.1 Shaft Access In a shaft-accessible mine, recharging and parking must be considered in the design. Typically, minimal consideration is given to parking locations at the end of shift because in general, diesel vehicles refuel during the shift and do not have specific parking requirements. Section 7.5.4 examines the trade-off between end-of-shift charging and battery swapping. Assuming end-of-shift charging, movement between the shaft station and BEV needs to be considered. Three key personnel transport methods are:

1. Walking
    a. BEVs are parked close enough to the shaft stations for personnel to walk to / from a BEV
    b. Requires sufficient parking locations and charger for all BEVs and sufficient power to supply chargers
    c. Likely not feasible for certain pieces of mining equipment (e.g., bolters and jumbos)
2. Personnel carriers
    a. Located near the shaft station to transport personnel to locations in the mine
    b. Can bring workers to parking locations
    c. Can bring workers to mining levels to reach mining equipment
    d. Consider charging personnel carriers near work areas once all personnel are delivered
3. Combination
    a. Flexible equipment (e.g., LHD machines, trucks, graders, and personnel carriers) is parked and charged near the station between shifts, and picked up by the workers as they exit the station at shift change

b. Slow movers or equipment typically dedicated to the mining zone (e.g., bolters and jumbos) are left in or near headings and workers are transported to them via personnel carrier

7.3.2 Ramp Access In a ramp-accessible mine, group travelling is strongly encouraged because long uphill travel at end-of-shift could deplete BEV batteries. It might be cost-effective to have dedicated group transportation BEVs carry personnel in and out of the mine; these are charged during shift. For downhill travel, a key consideration is regenerative braking: to prevent over-charging the battery or over-using the mechanical braking system, BEVs need to enter the ramp with a partially depleted battery to absorb all regenerative braking energy. Figure 11 illustrates the personnel transport options that affect battery size requirements of a BEV.

7.4 Other Electric Equipment

Each type of electric equipment has a different charging configuration.

7.4.1 Charge-While-Operating Equipment Group (Tethered) Charge-while-operating equipment is typically plugged into AC power while performing work, and travels under diesel or battery power when moving between work locations. This group typically includes:

- Bolters / cable bolters
- Scalers
- Jumbos
- Production drills
- Mobile raisebore units
- Explosive loaders
- Shotcrete sprayers

Because it operates under AC power most of the time, charge-while-operating equipment requires a smaller capacity battery for travel periods only. In addition, the trailing cable presents an opportunity to install batteries that charge while the equipment is plugged in to AC power. If all charging is accomplished via an on-board charging system, no external chargers are required. If an on-board charger is lacking, additional portable chargers are required close to the face because the cable length is limited between the charger and the equipment.

The duty cycle of the battery on each piece of equipment must be reviewed to calculate the charge frequency, which can then be used to determine the number of chargers required on each mining level (Section 11.2.1). This exercise makes it apparent that off-board charging becomes a very expensive option that also increases the complexity and decreases the efficiency of the mining cycle. Therefore, efforts should be made to ensure on-board charging with charge-while-operating equipment.

7.4.2 Trucks The following options currently exist for ore / waste movement by truck:

- Regenerative braking
- Swap-out battery vs. in-shift charging vs. end-of-shift charging
- Inductive and trolley-assist charging
- Hybrid-powered options

7.4.3 LHD Machines Mine design considerations that affect LHD machine performance include:

- Mine-level grades relative to energy consumption
- Swap-out battery vs. in-shift charging vs. end-of-shift charging
- Inductive and trolley-assist charging
- Hybrid-powered options
- Fully tethered electric options

7.4.4 Alternate Haulage Methods Alternate haulage methods include conveyors, electric-powered trains, trolleys, and monorails, RailVeyor™, and continuous haulage systems.

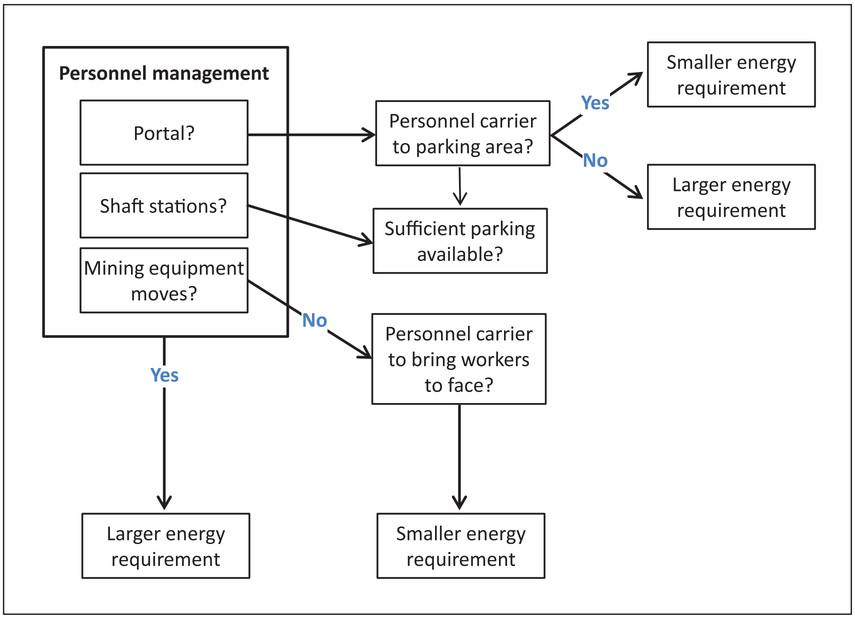


Figure 11. Simplified Personnel Management Impact on Battery Sizing

7.4.5 Auxiliary Vehicles Support or service vehicles include scissor-lifts, transmixers, forklifts, boom trucks, mechanic trucks, and graders, which lend themselves well to battery conversion. However, considerations for parking and charging requirements must be addressed.

The electric fleet design sections above are illustrated and summarized in Figure 12.

7.5 Charging Infrastructure

Once the personnel transport needs are determined, the equipment is chosen, and the mine is generally laid out, the charging infrastructure can be defined. Mine operations will depend on the availability of fully charged batteries; therefore, sufficient design in the charging system is crucial. The charging philosophy (Section 6) and factors depicted in Figure 13 will influence the mine layout and must be considered.

7.5.1 Design Prerequisites The required excavation footprint and support services depend on the following:

- Number and duration of underground shifts, typically in hours per day
- Expected running time for the equipment—with input from equipment vendors—based on size and required duty per shift (accounting for personnel travel time, breaks, set-up, and other battery downtime)
- Equipment duty cycle
- Based on the equipment fleet, number of charging stations and types of chargers (described in detail in Section 6) required throughout the mine and their locations
- Whether opportunity charging will be employed (Section 7.5.4)
- Preference for battery charging in-shift, at end-of-shift, or through battery swapping for each piece of equipment
- Whether the auxiliary fleet will be able to complete a shift cycle without requiring a charge. Some equipment may have small batteries or require specific chargers (e.g., a grader that cannot reach all areas of

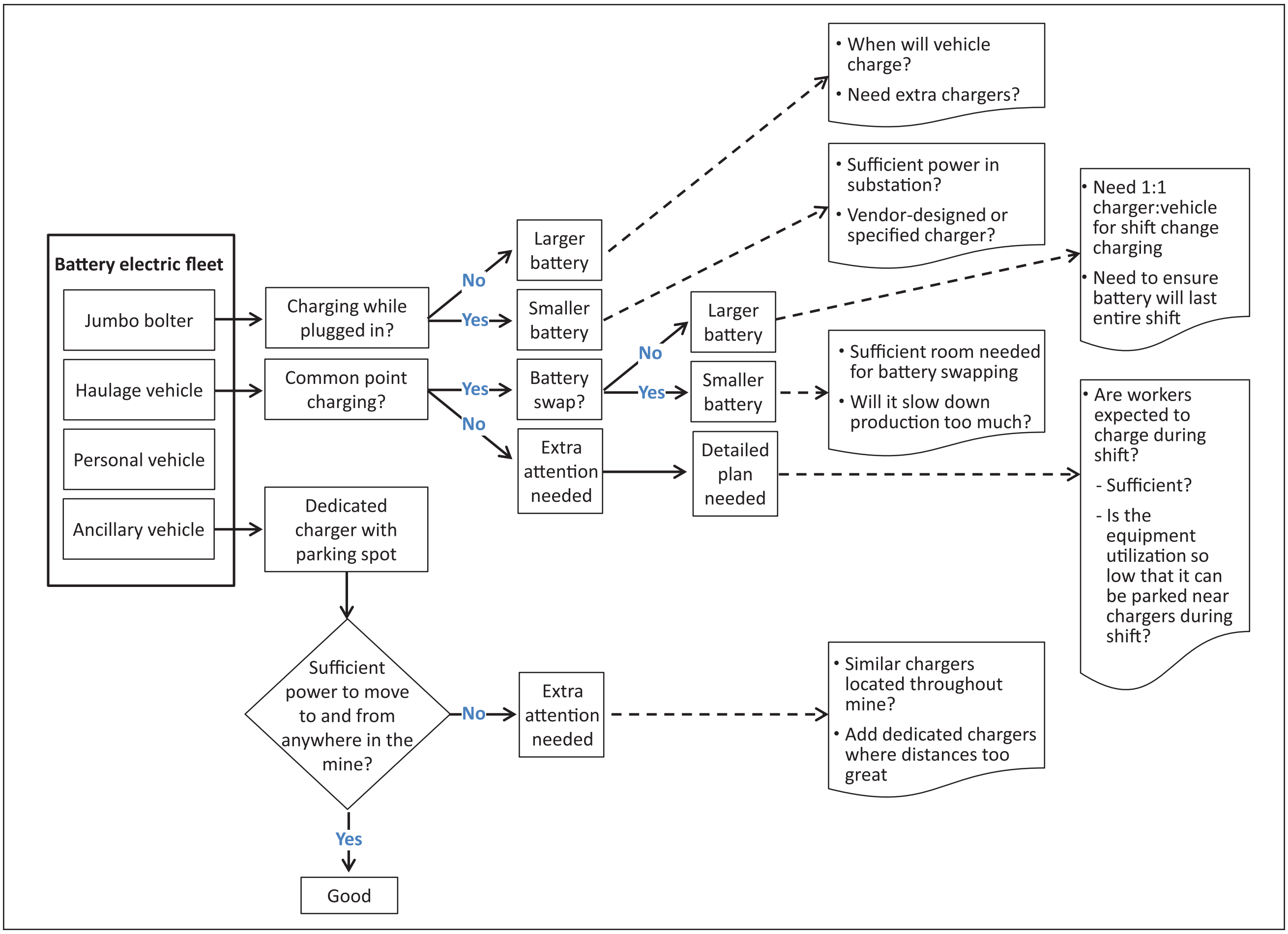


Figure 12. Electric Fleet Design Considerations

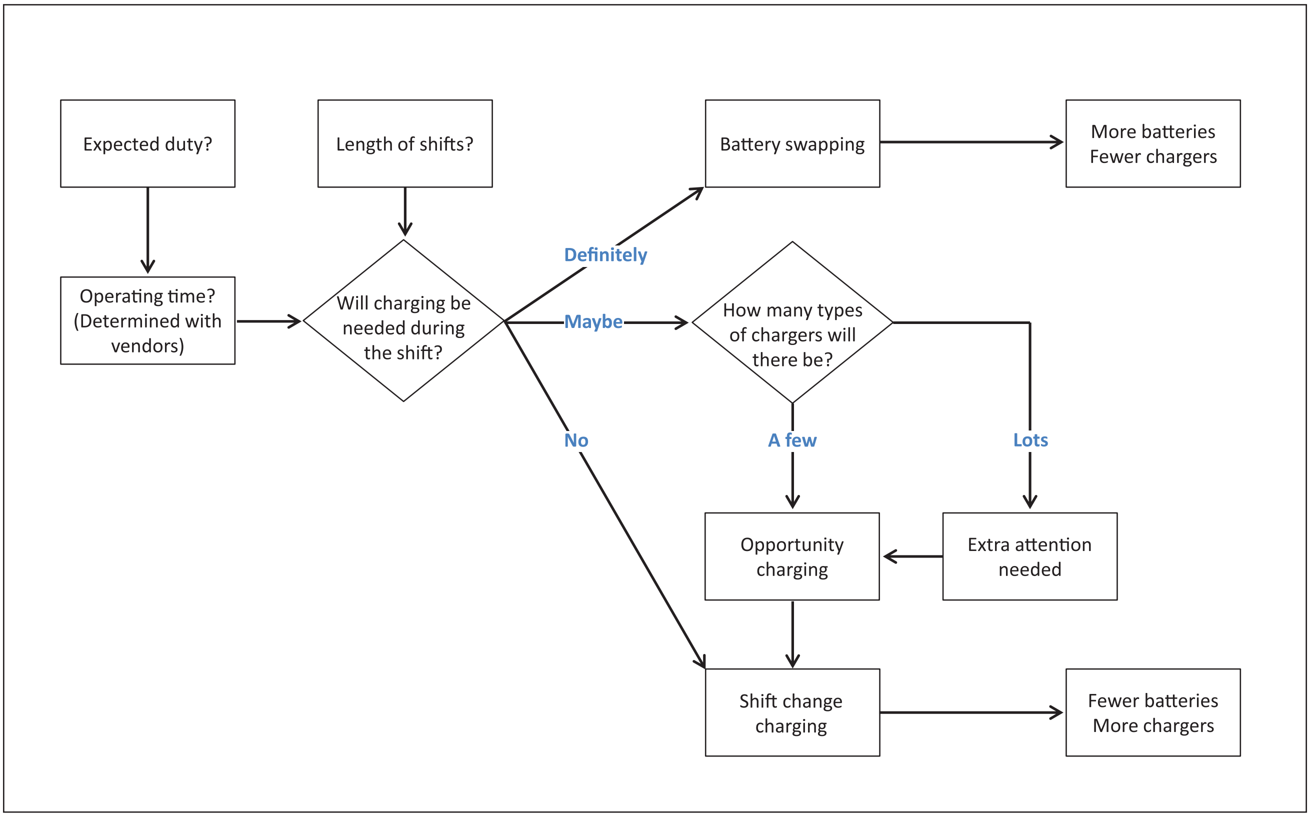


Figure 13. Charging System Design

the mine from its parking / charger location and uses a specific charger will need a second charger placed strategically in the mine). These situations should be avoided if possible.

7.5.2 Charging Method The following points should be considered when developing a charging philosophy:

- If the battery running time is longer than the shift length at the design duty, then shift-change charging is simple to implement.
- If the battery running time is marginally shorter or longer than the shift length at the design duty, then shift-change charging with opportunity charging or battery swapping could be implemented.
- If the battery running time is substantially shorter than the shift length, then alternate methods would likely be a necessity, such as battery swapping or in-shift charging.
- As technology advances, other methods of charging such as trolley-assisted, inductive, or other advancing technologies may become more prevalent.

7.5.3 Charger Diversity Multiple charging philosophies are currently in use; selecting the appropriate one for a given application will be a key parameter for successful implementation of a fully electrified mine. Efforts to standardize should be pursued. The simplicity found in diesel fuel made implementation effortless, any piece of equipment sent underground simply needs to be filled with fuel and "away it goes" (Section 6).

7.5.4 Opportunity Charging The use of opportunity charging to top up batteries in-shift (i.e., during downtimes such as breaks) may not be a good business decision. If both end-of-shift and opportunity chargers are installed, project costs would significantly increase. Calculating the cost per charger, opportunity duration, and amount of energy transferred to the battery will ensure economic viability before full-scale redundant chargers are installed. The scenarios below—based on the assumption that the mine is running two shifts—can facilitate determining the feasibility of implementing opportunity charging.

Charging time scenario 1: Basic scenario
Opportunity: 2 × 30 min. lunch break + 6 × 10 min. bio break = 2 h/day
Typical shift-change: 2 × 2 h/day = 4 h/day

Therefore, an opportunity charger provides half the charger utilization of a shift-change charger.

Charging time scenario 2: Stagger lunch breaks, use end-of-shift charger
Opportunity: 4 × 30 min. lunch break + 6 × 10 min. bio break + 4 h end-of-shift = 7 h/day
Typical shift-change: 4 h/day
Therefore, an opportunity charger could provide greater charger utilization than a shift-change charger, with sufficient coordination.

Energy transfer to battery scenario 1: 50 kW charger and 100 kW battery
Opportunity: 30 min. lunch break = 25 kW power (approx. 25% charge)
Typical shift-change: 2 h between shifts = 100 kW power (approx. 100% charge)
Good option for BEVs that are expected to run out of power before end-of-shift

Energy transfer to battery scenario 2: 100 kW charger and 100 kW battery
Opportunity: 30 min. lunch break = 50 kW power (approx. 50% charge)
Typical shift-change: 2 h between shifts = 200 kW power (approx. 100% charge)
Good option to decrease battery size, power requirements at shift change, and “range anxiety” for workers

Among design considerations for charger locations, the highest priority should be given to accessibility and maximizing charging time. BEVs that are not operating should be charging. If two chargers are located near a lunch room, only two BEVs can be charged; other BEVs will not benefit from opportunity charging.

7.5.5 Charging Station Layout Because BEVs are not common underground, not all individuals are familiar with the concept. For non-electrical designers, chargers can be compared to typical variable frequency drives (VFDs) in ventilation systems.

7.5.5.1 Physical environment The physical environment considerations described below are illustrated in Figure 14.

Chargers contain sensitive electronics; therefore, they must be treated with care to survive for sustained amounts of time in harsh mining environments, which contain:

- Dust
- Humidity
- Heat (see Section 7.6 for ventilation design to remove excessive heat)
- Vibration
- Percussion blast
- Water via failed pipes, dripping from the back, or partial flooding in the area
- Physical barriers to prevent vehicle collisions such as bollards and walls

7.5.5.2 Spacing and parking Equipment spacing should follow OEM recommendations and local regulations. Charging cable maneuverability is a key consideration: depending on the chosen technology, the cable length between chargers and connection points on BEVs could be restricted by cable size (i.e., voltage drop) or communication protocols (e.g.,

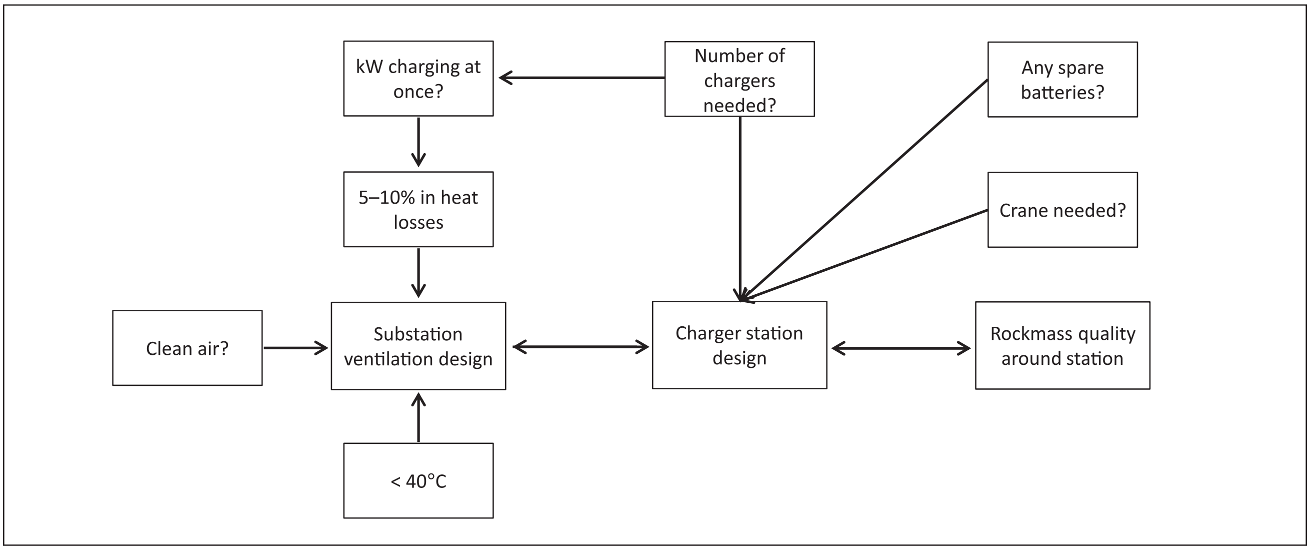


Figure 14. Charging Station Design Considerations

RS-232, Ethernet). Larger cables or different protocols could remove these restrictions, but at a cost that could outweigh the benefits.

7.5.5.3 Battery swap-out station design Similar to a typical diesel refueling station, a battery swap-out station should allow a BEV to enter, be recharged by an instructed person (International Electrotechnical Commission, 2004), and leave in a short period of time with a charged battery. The logistical plan for scheduling battery swap-out should be an input to the design. Additional particularities of a battery swap-out station include:

- Crane system to remove and install batteries on equipment and move batteries within the station
    - Must be compatible with all BEV types that will use this system
- Charger in proximity that has sufficient charging capabilities based on the quantity of spare batteries
- Sufficient spare batteries that are charged, charging, or depleted
- Significant excavation requirements that may pose a risk to rockmass quality and hydro-geotechnical conditions

7.5.5.4 Mine power distribution considerations Because most chargers operate with an incoming voltage of 480–1,000 V, three phases, the distribution equipment must be located within an acceptable distance (i.e., 75 m for 600 V) of the chargers to ensure system strength. Chargers are harmonic producing devices (Section 10.4). Therefore, a stiff system—with high available fault power and good voltage regulation—is ideal for the operation of multiple devices without interference. As a rule of thumb, such systems should be able to provide a fault current that is approximately 20 times the full load amperage (FLA) of the charger. For example, for a 50 kW charger with 5% losses, the FLA would be approximately 50.5 A on a 600 V system and should be connected on a network able to provide 1 kA of fault current. If two 400 kW chargers are to be connected on a common bus, the combined FLA is 808 A and requires a system capable of delivering 16 kA at 600 V. This may seem to be a high value, but it is typical for a 1 MVA transformer, as long as the impedance between the transformer and the chargers is not significant.

Transformer size selection is generally based on the mining equipment expected to operate simultaneously in an area and other loads (e.g., ventilation fans, dewatering pumps, and lights) that are required to support the advancement. Sizing a transformer in an all-electric mine needs to consider the operation of chargers. It is imperative to keep in mind the charging philosophy (Section 6) to prevent over-sizing transformers.

7.6 Ventilation and Cooling

A ventilation study must address and deliver solutions for safety and technical aspects, as well as fit the mining methods and OWHS options. An iterative approach between the mine and ventilation designers will produce a design that is robust and economical.

A set of design criteria provides a structured approach to satisfying a good engineering design. The design criteria will be the same for an electric mine as a diesel mine (e.g., temperature, dust, and air velocity targets), but some aspects of the criteria will differ (e.g., an electric mine need not comply with diesel particulate matter regulations).

Designs are based on battery limits and constraints such as mine life, capital, geology, OWHS, production profile, type and level of automation, mining method, environmental considerations, and jurisdictional legislative requirements. Deliverables from a design would include determining the air volumes and an air distribution system with all required infrastructure and controls (Tables 2 and 3).

7.6.1 Determining Air Volume The process for determining air volume for battery-powered mobile equipment is based on heat, dust, and air velocity (Figure 15), whereas for diesel-powered equipment, it is based on diesel particulate matter, heat, and gas dilution, and is often dictated by government regulations. The sections below describe parameters specific to an electric mine.

7.6.2 Regulations Federal and local regulations applicable to the mine site jurisdiction and internal mining company standards must be determined before beginning mine design. Mobile equipment activities create dust and heat that significantly influence the air volume and the associated distribution. Air quality regulations and standards will influence air volume requirements.

7.6.3 Equipment Fleet The equipment fleet is based on the production profile and is a key parameter for determining mine heat loads. The mine plan designer must work with the equipment vendor(s) to optimize the fleet and equipment size for the proposed mine layout and production schedule.

7.6.4 Heat Load The mine heat load is determined by summing—for each mine level—the contribution of heat from major sources such as fixed electrical equipment (e.g., mine load centres, fans, pumps, and chargers), mobile equipment (diesel vehicles, BEVs), auto compression, and wall

Table 2. Air volume design data needs, sources, and applications for electric equipment

Need	Source	Application
Jurisdictional air quality regulations	Federal, local, and company standard threshold limit values	Drive final air volume and distribution calculations to dilute dust, emissions, and heat generated by mobile fleet
Equipment fleet required throughout affected area or mine	Based on production profile and equipment capacity	Mine heat load and dust calculations Size and number of BEVs may differ from diesel fleet
Motor power and expected duty cycles of equipment	Basic data on equipment data sheet from equipment vendors May need more specific information for a given application	Mine heat load calculations
Area heat loads from equipment based on motor output, efficiency, and duty profile	Load/power profile curves from equipment vendors based on a variety of operating scenarios	Air volume calculations to dilute heat
Heat loads from charging stations / areas	Equipment vendors	Air volume calculations to dilute heat Heat from charging + heat from equipment = total heat load
Dust loads from mining activities	Monitoring database at sites	Air volume and/or minimum velocity calculations to dilute dust Use in conjunction with historic dust concentrations at the site

Table 3. Ventilation design data considerations, sources and applications for electric equipment

Consideration	Source	Application
Required air way opening dimensions	Federal, local, or company guidance	Design infrastructure based on air volume required to dilute heat or dust (whichever higher)
Ensure air velocities from airway opening and air volumes within limits	Federal, local, or company guidance	Low velocities affect blast clearing times High velocities can create dust hazards
Does heat require maximum ventilation rates?	Federal, local, or company guidance	Are workplace temperatures too high?
Can additional air volume dilute the heat?	Study on cost of larger infrastructure or	An economic analysis to determine if a refrigeration plant is required
Fixed monitoring for dust, gas and/or heat	Federal, local, and/or company guidance	Depends on mine operator preference and air distribution system type and maintenance needs Mandatory if controlled recirculation is part of the ventilation system
Will air be re-circulated?	Jurisdictional regulations or company standards	With zero-emission electric equipment, controlled recirculation may be a solution to reduce total mine volumes as long as contaminant concentration levels are met
Determine hazards that could affect the ventilation infrastructure, rescuability of personnel, and high risk zones for fire	Risk assessment	Address high risks with redesign of mine layouts, infrastructure, and air path, and direction

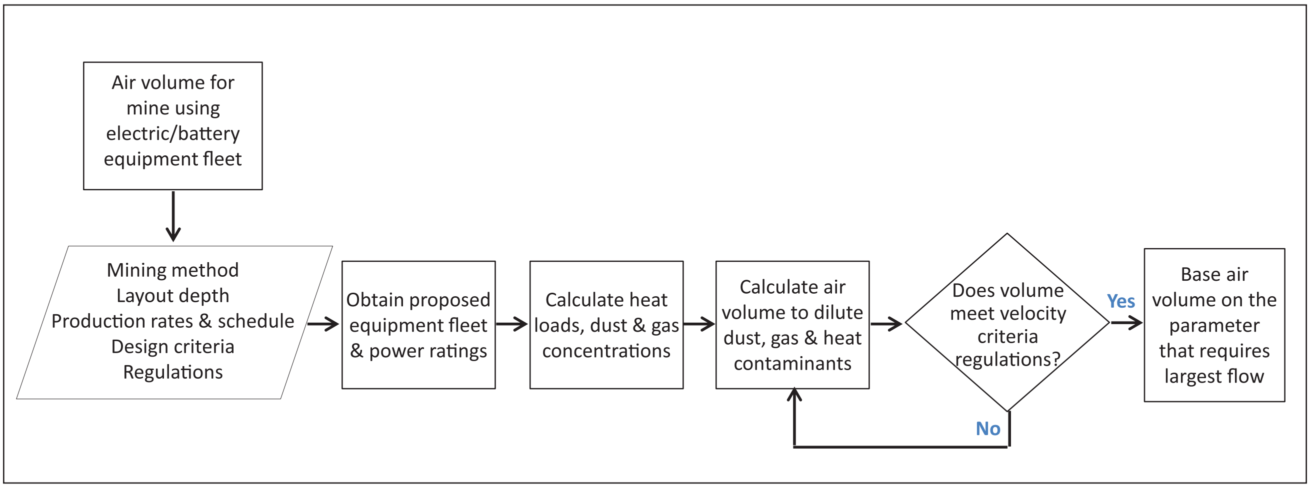


Figure 15. Air Volume Sizing Process for Battery-Powered Mobile Equipment

rock. Auto compression and wall rock temperatures increase with depth; therefore ventilation rates in mines with hot conditions increase on each deeper level.

Once the heat load is determined, the air volume required to dilute the heat can be calculated. Because BEVs are considered to have zero emissions, the air volumes can be lowered, which may result in elevated temperatures. An analysis may be required to determine the optimum ventilation volumes with or without introducing refrigeration. Several software packages can assist in the calculation of mine total heat loads, typically in kW. Care must be taken to control the quality of information entered into the solvers.

7.6.4.1 Heat from mobile equipment The heat load from mobile equipment is determined from the motor power output considering different work duties. The first step is to list the equipment power for both diesel and electric mobile equipment that may be typically active on the level at the same time. Then, factors are applied to account for efficiency, usage, work rates, and gradient. For diesel equipment, the thermal efficiency of the engine is approximately 30%: a significant portion of the power becomes heat whether the engine is loaded or idling. An electric motor is very efficient: heat generation equals the power consumed (Hamlin & Kerai, 2013). Load/power profile curves from the BEV vendor would facilitate determining the equipment kW ratings for the heat load determinations.

7.6.4.2 Heat from charging Typical heat losses from charging equipment are 5–10%, but equipment vendors must provide estimates of heat generated when chargers are operating for a given rate and method. Depending on the charging philosophy and placement of chargers, special attention should be paid to the exhaust path of this heat and placement of infrastructure.

One 50 kW charger operating with 5% losses for 1 h would generate 2.5 kW of heat in the charging area, which can be considered marginal. Four 400 kW chargers operating in the same area with 10% losses for 1 h during a shift change would generate up to 160 kW of heat in the charging area during the one hour charge period. Therefore, it is important to consider the impact of chargers on heat loads, keeping in mind that chargers do not operate 24 h/day. It is crucial to ensure chargers are provided with a reasonable means of cooling, so that air temperature in the charging area are below 40°C dry-bulb, to prevent electronic failures (Section 10.3).

7.6.5 Dust Dust is a key criterion to establish air volumes in an electric mine. Dust contaminant removal depends on the air velocity, but air speeds that are too high can create hazards:

- Large dust particles become airborne and cause eye injuries
- Extended exposure to moving air causes eye irritation
- Moving air increases worker physical exertion

Air velocities that are too low do not remove and dilute heat or small respirable dust particles, and can also reduce visibility. Drift size, air volume, and/or recirculation of air should be re-examined. Target design air velocities must be established within the design criteria for different infrastructure and work areas (e.g., working face, conveyor drifts, and haulage routes).

Baseline dust loads can be determined from historical mine site data from the mine occupational exposure monitoring program. These data can be used to determine dust sources and concentrations from mining processes and mineralization. Once the air volumes are determined from established target velocities, dilution calculations can determine if the volumes dilute dust concentrations to acceptable levels.

7.6.6 Developing the Ventilation Design and Plan Unlike a greenfield site, conversion to electric equipment at a brownfield mine means that air velocities may become problematic and the opportunity for alterations to existing infrastructure may be limited.

The positive impact of the electric mine will emerge during ventilation design development (Figure 16), evidenced by little ventilation infrastructure relative to a diesel mine. Primary ventilation system components such as fans, raises, and transfer drifts will be reduced, as well as auxiliary system fans and ducting. Placement of infrastructure such as intake and return paths must accommodate parking and charging areas. The air heated from chargers may be considered "used" from a temperature perspective, but it will be very clean and dry. In the scenario of shift-change charging, heated air could easily be re-used for blast clearing and/or to warm cold mine air.

7.6.6.1 Airway sizing The air volume requirements for heat and dust dilution must be compared and airways sized to economically accommodate the larger of the flow requirements. Facilities such as garages and leakage paths throughout the mine from various control devices should be included in final air volumes. Airway sizing proceeds iteratively until needs such as refrigeration are determined (Section 7.6.6.2). Airway placement will need to consider conditions unique to an electric mine layout, such as number and size of substations and charging stations.

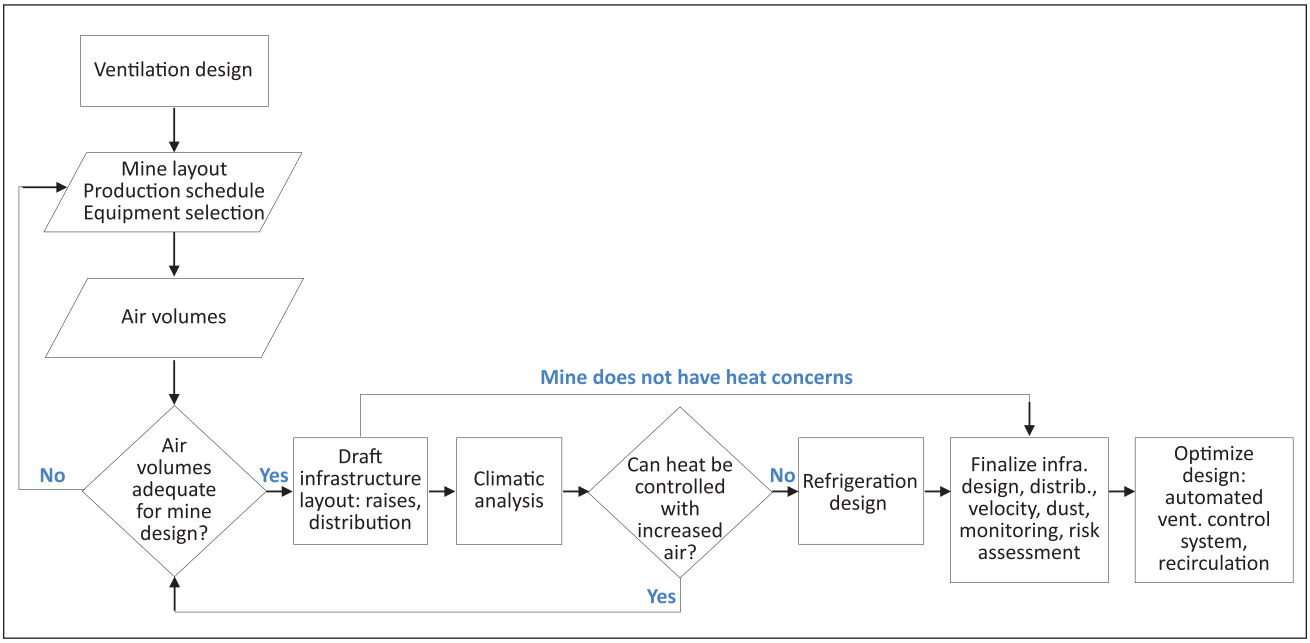


Figure 16. High-Level Ventilation Design Process

7.6.6.2 Heat If the heat load generated in the mine will approach or exceed any design criteria temperature limits (i.e., workplace, intake, or reject), a study must be completed to determine if additional air volume can dilute the heat, or if mine air cooling is required. The study results will be based on the mine schedule impact and economics of larger ventilation infrastructure to meet the design temperature criteria vs. the cost of a refrigeration system. If a refrigeration system is the selected option, air volumes will be reduced throughout the system. Therefore, air velocities throughout the mine will need to be confirmed that they remain within the design criteria limits.

7.6.6.3 Blast gas clearing The time required to clear blasting fumes from the face through the path to exhaust depends upon the air speed. In an electric mine, the opportunity to reduce air volume may create a low air velocity condition, which would protract the blast clearing time and delay personnel getting to the workplace. A review of the clearing time should be conducted once a preliminary ventilation design is completed to highlight any problem areas. Consideration should be given to include controls in the design to allow the air velocity to be increased after a blast in affected areas. Options could include variable speed drives on fans and automated ventilation control systems.

7.6.6.4 Monitoring A mine site must determine if real-time monitoring of the underground environment or ventilation controls will be part of the mine design. This decision, as well as what will be monitored and why, will influence the placement, resolution, and type of monitoring instrumentation. If underground fixed monitors are installed, it is recommended to communicate the signal to a surface human-machine interface and set up for trending. A significant factor in the decision for fixed monitoring is the ability to calibrate and maintain the system.

Fixed monitoring systems are generally installed underground for detecting heat and gases that commonly occur and for which reliable sensors exist (e.g., carbon monoxide, sulfur dioxide, and nitrogen oxides). Additional monitoring may also be required based on battery chemistry. Carbon monoxide is a good surrogate indicator for potential environmental issues. Heat monitoring instrumentation commonly measures dry-bulb temperature and relative humidity; wet-bulb temperature is calculated from these values and the barometric pressure. Currently, dust is not commonly measured in real-time.

7.6.6.5 Controlled recirculation Although it has been studied for many years, application of controlled full or partial recirculation is limited in a ventilation system design because of safety and health implications from typical mining methods and hazards. Electric mine design presents an opportunity to use controlled recirculation because electric equipment produces little dust, heat, and gas. If controlled recirculation were part of the design, fixed monitoring would be required to ensure regulatory compliance of air quality.

7.7 Safety

A high-level risk assessment is recommended to evaluate the total mine risk from converting diesel to electric and highlight potential hazards specific to the ventilation design. Safety training (operator, maintenance) is an essential component. Other safety considerations include:

- Noise
- Power and voltage
- Air quality (diesel particulate matter, dust, and moisture)
- Heat
- Fire
- Geotechnical

An electric mine has different energy sources than traditional mines and areas where large numbers of equipment are concentrated for parking or charging. It is necessary to understand the potential for fire in the electric mine and the rescue-ability of personnel. The adoption of BEVs can reduce the potential for fire by minimizing or removing diesel fuel from underground and hot engine sources of ignition. However, there are unique issues associated with fighting a fire on a BEV, which should be identified (i.e., special labeling) to protect mine rescue personnel from harm. Depending on the battery chemistry, uncommon gases could be released into the general atmosphere during normal operation, charging, and fire that must be recognized in the mine design (Section 9.1).

8. BATTERY ELECTRIC VEHICLE DESIGN

8.1 Introduction

In addition to a large electric motor, BEVs comprise an operator interface, braking system, electrical system (including the battery and BMS), and in some cases, an on-board charging system (Section 6.1). Depending upon the design, a given BEV may use:

- A transmission
- A clutch, gearbox, differential, and fixed gearing
- Battery packs and motors

Overall, BEV design must integrate the strong relationship between the design of the electric motor and of the other BEV components.

8.2 Operator Interface

The symbols for operator controls and displays should be designed in accordance with current versions of ISO 6405-1:2017 and ISO 6405-2:2017 (Table 4). The BEV operator interface is the site of human-machine interaction, and thus is critical to correct and safe BEV operation. The operator interface should visually display information about the battery SOC to the operator at all times, since the SOC determines the remaining distance before recharge is required. Visible and audible signals are also part of the operator interface, for example, a manual alarm to alert personnel that the BEV is underway (e.g., FMVSS 141, Table 4) or an automatic alarm to alert the operator that the SOC is at a critical level or the insulation resistance is low.

The SOC is also strongly linked to the regenerative braking system that returns energy to the battery when the BEV is braking, coasting, or going downhill. If battery or drivetrain parameters (e.g., temperature, current, voltage, or SOC) reach a critical level, the system must be capable of initiating visual and audio alarms to the operator. If the SOC or temperature prevents the battery from absorbing the regenerative energy, the operator must be warned if the vehicle braking performance will be impacted. This is particularly important if service brakes use only regenerative energy and their capacity is affected by the battery SOC. Alternatively, the regenerative braking functionality can be automatically turned off before the battery SOC limits brake capacity (Section 8.3.1). The regenerative braking state (on or off) should always be clearly displayed on the operator interface.

8.3 Braking System

The BEV should have a service brake, secondary braking, and parking brake system, as defined in ISO 3450:2011 and CAN/CSA-M424.3-M90 (R2016) (Table 4), or the applicable regional standard. The braking system should be tested in accordance with both of these standards. The braking system circuit should be designed in accordance with ISO 13849-12015 and ISO 3450:2011, and tested in accordance with ISO 13849-2:2012.

8.3.1 Resistive braking If an OEM is considering using resistive braking as the only source of service braking, the BEV should meet the requirements detailed in the applicable standards, for example ISO 3450:2011 or CAN/CSA-M424.3-M90 (R2016) (Table 4).

If the battery SOC affects the capacity of the service brakes in any way, the BEV should consider a means of manually or automatically turning the regenerative braking off when the capacity of the regenerative braking cannot effectively stop the BEV.

8.4 Electrical Systems

Safety data sheets for the BEV battery system should be made available by the OEM. Electrical systems should be designed in accordance with ISO 14990-1:2016, ISO 14990-2:2016, and ISO 14990-3:2016 (Table 4). Applicable local

Table 4. Names, topics, and jurisdictions of standards related to BEV design, listed in the order they are cited in this section. Full standard citations are listed in Section 13.

Recommended Industry Standard	Topic	Jurisdiction	Citation
ISO 6405-1:2017	Standardizes symbols on operator controls and other displays on multiple types of earth-moving machines as defined in ISO 6165:2012	International	International Organization for Standardization, 2017a
ISO 6405-2:2017	Standardizes symbols on operator controls and other displays on specific machines, equipment, and accessories as defined in ISO 6165:2012	International	International Organization for Standardization, 2017b
ISO 6165:2012	Terms and definitions and identification structure to classify earth-moving machines	International	International Organization for Standardization, 2012a
FMVSS 141	Minimum sound requirements for BEVs to warn persons that BEV is underway	USA	United States National Highway Traffic Safety Administration, 2013
ISO 3450: 2011	Minimum performance requirements and test procedures for service, secondary, and parking brake systems of wheeled and high-speed, rubber-tracked earth moving machines	International	International Organization for Standardization, 2011a
CAN/CSA-M424.3-M90 (R2016)	Minimum performance criteria for the service braking, secondary braking, and parking systems for rubber-tired, self-propelled underground mining machines	Canada	CSA Group, 2016a
ISO 13849-1:2015	Safety requirements and guidance on design and integration of safety-related parts of control systems, including software	International	International Organization for Standardization, 2015b
ISO 13849-2:2012	Procedures and conditions to validate—by analysis and testing—specified safety functions, the category achieved, and the performance level achieved by the safety-related parts of a control system designed in accordance with ISO 13849-1:2015	International	International Organization for Standardization, 2012b
ISO 14990-1:2016	General safety requirements for electrical equipment and components incorporated into earth-moving machines as defined in ISO 6165:2012	International	International Organization for Standardization, 2016a
ISO 14990-2:2016	Safety requirements for electrical equipment and components incorporated in externally-powered (mains-connected or dedicated generators), electrically-driven earth moving machines	International	International Organization for Standardization, 2016b
ISO 14990-3:2016	Safety requirements for electrical equipment and components incorporated in self-powered (utilizing on-board electric power sources) electrically-driven earth moving machines	International	International Organization for Standardization, 2016c
ISO 13766:2006	Test methods and acceptance criteria for evaluating the electromagnetic compatibility of earth moving machines as defined in ISO 6165:2012	International	International Organization for Standardization, 2006
ISO 15998:2008	Performance criteria and tests for functional safety of safety-related machine-control systems using electronic components in earth moving machines and equipment as defined in ISO 6165:2012	International	International Organization for Standardization, 2008
IEC 60068-2-6:2007	Standard procedure to determine the ability of components, equipment, and other articles to withstand specified severities of sinusoidal vibration	International	International Electrotechnical Commission, 2007
IEC 60050-826:2004	Vocabulary related to electrical installations on residential, industrial, or commercial premises	International	International Electrotechnical Commission, 2004
E/ECE/324/Rev.2/Add.99/Rev.2	Safety requirements of vehicle electric power train	International	United Nations, 2013
ISO 13850:2015	Functional requirements and design principles for the emergency stop function on machinery, independent of the type of energy used	International	International Organization for Standardization, 2015
IEC 60204-1:2016	General safety requirements of electrical, electronic, and programmable electronic equipment and systems to machines not portable by hand while working	International	International Electrotechnical Commission, 2006b
UL 2231-1	Requirements to reduce the risk of electric shock to the user from accessible parts in grounded or isolated circuits (external to or on-board) for charging BEVs	USA	UL, 2012a
ISO 6469-3:2011	Requirements for electric propulsion systems and conductively connected auxiliary electric systems of electrically propelled road vehicles for the protection of persons inside and outside the vehicle against electric shock	International	International Organization for Standardization, 2011b
ST/SG/AC.10/11/Rev.5	Criteria, test methods, and procedures for classifying dangerous goods	International	United Nations, 2009
ST/SG/AC.10/1/Rev.17	Model regulations on the transport of dangerous goods	International	United Nations, 2011

codes should also be reviewed and followed. To ensure BEVs do not adversely affect nearby equipment, communication devices, or other microprocessor-controlled devices, they should be designed to meet the intent of ISO 13766:2006 (Table 4), which outlines requirements and limit values for electromagnetic emission and immunity to external electromagnetic fields, as well as the procedure and criteria for testing machinery and associated electrical / electronic systems.

The BMS should be integrated into the BEV design to monitor critical battery operating conditions (e.g., temperature, SOC), which would be defined by the type of battery, the battery manufacturer, and the system integrator or OEM. The BMS communicates with charging infrastructure and emergency shutdown subsystems (Sections 9.1–9.3).

8.5 Shock and Vibration

BEVs should be designed to meet shock and vibration profiles that align with the anticipated use environment. As a minimum, the requirements of ISO 15998:2008 or IEC 60068-2-6:2007 (Table 4) should be met.

8.6 Fire Suppression

BEVs should have a fire suppression system appropriate for the vehicle type. Automatic systems should be capable of being manually activated by the BEV operator.

Fire-fighting information to train operators, mechanical personnel, electrical personnel, and first responders must be provided by the OEM. These individuals require distinct training / qualification levels within their own category to efficiently and safely undertake tasks of varying degree of risk.

8.7 Accessibility and Service

OEMs and vendors should provide recommended schedules and procedures for inspecting and maintaining BEVs and their components. BEVs intended for use in mines should be rugged in construction and designed to facilitate inspection and maintenance by a skilled person as defined in IEC 60050-826:2004 (Table 4).

- Components arranged for easy access for inspection and maintenance
- Lifting points for heavy components, located such that cables/chains do not interfere with other components
- Proper clearance for inspecting and maintaining of components
- Access openings in enclosures located only where necessary for maintenance or inspection
- High-voltage components separated from lower voltage components
- In enclosures where access is for maintenance personnel: barriers, partitions, and covers provided and arranged so that testing and troubleshooting can be safely conducted
- Covers as lightweight as is feasible (i.e., < 1 kg)
- If covers cannot be lightweight, consider using hinged covers with a handle and warning label
- Pinch points eliminated if possible
- Appropriate signage attached for service
- Signage to discourage welding or other modifications to the battery and electrical system
- In the event that a hazardous voltage enclosure can be opened without tools, it should comply with Section 5.1.1.3 of E/ECE/324/Rev.2/Add.99/Rev.2 (Table 4) or be touch-safe

8.8 Emergency Stop

A BEV energy storage system can present inherent hazards and risks: if they cannot be eliminated or when the risks cannot be sufficiently reduced by safe design, an emergency stop function should be included in the BEV design that complies with ISO 13850:2015 (Table 4), which deals with safety aspect(s) or one or more types of safeguard that can be used across a wide range of machinery.

8.9 Master Disconnect

A BEV should incorporate one or more manual master disconnect devices. A master disconnect device completely de-energizes a BEV for service or storage. When activated, it physically disconnects all high- and low-voltage sources of electrical energy to the BEV controls and traction system, including protective functions such as fire suppression and vehicle entrapment prevention. The master disconnect is not required to disconnect electrical connections internal to the battery system. A master disconnect device incorporates lockout / tagout capability.

8.10 Insulation / Ground Fault Monitoring

High-voltage energy is always present in a vehicle battery system. Insulation systems between the high-voltage battery bus and the vehicle chassis protect operators, technicians, and service personnel from potential shock hazards (e.g., IEC 60204-1:2016, UL 2231-1, and ISO 6469-3:2011; Table 4). If the insulation system breaks down or if the electrical system is compromised, there is a potential risk of electric shock to personnel in contact with the vehicle.

A BEV should include an insulation monitoring system to alert personnel to the risk of electric shock due to a compromised high voltage electrical system. An insulation monitoring system continuously monitors the path between the high-voltage electrical system and the vehicle chassis. It alerts personnel that there is a risk of electric shock if a person comes in contact with a high-voltage conductor and the vehicle chassis. If insulation resistance drops below a predetermined value (typically 100 ohm/V based on the nominal voltage of the battery system), a visual and audible indicator or alarm is activated.

The insulation monitoring system may be tested by connecting an OEM-recommended test impedance between any point on the high-voltage bus and vehicle chassis (e.g., ISO 14990-1:2016). If the insulation monitoring system is working properly, an indicator and/or alarm will become active when the test impedance is applied. Upon detection of an insulation fault, the vehicle should be inspected and repaired by trained service personnel as soon as possible.

8.11 Additional Safety Recommendations

Safety encompasses all components of the BEV for the full lifecycle, from commissioning to decommissioning. Therefore, these recommendations are categorized according that cycle. Standards ISO 13849-1:2015 and ISO 13849-2:2012 (Table 4) cover overall risk assessments.

8.11.1 BEV Design BEVs should be designed to avoid operating modes or sequences that can cause a fault condition or component failure leading to a hazard. Components should be selected based on the expected stress levels encountered during the lifetime of the BEV. Stress factors include mechanical vibration, low and high temperatures, low and high humidity levels, presence of conductive contaminants and pollution, and the presence of water or corrosive environments.

Energy storage systems—whether within or outside the BEV—should be protected against fault current and over-current. An over-current protective device should be in close proximity to the energy storage cells and should not require a current greater than the fault current available to open. The over-current protective device should be rated to interrupt the maximum fault current available from a fully charged energy storage system.

BEV design should allow for an interlock device to prevent movement of the BEV while connected to the power source, unless the BEV is designed to operate while plugged in (e.g., jumbos).

8.11.2 BEV Operation BEVs are extremely quiet while operating, which represents an advantage over traditional diesel equipment (Section 5.1), but also presents a safety hazard to personnel near the BEV. BEV design should incorporate warning sounds that can be triggered manually (e.g., horn) or automatically for BEVs travelling in forward or reverse. This has been mandated to protect pedestrians in the United States for OEMs of commercial hybrid vehicles and BEVs (FMVSS 141, Table 4).

The OEM is responsible for providing means and procedures to remove BEVs stopped due to malfunction or loss of power.

See Section 9.2 for operating procedures related to battery exchange and charging.

8.11.3 BEV Maintenance As noted in Section 8.10, high-voltage energy is always present in a vehicle battery system. Components may contain capacitors or other devices that do not immediately dissipate charges. Even when turned off or de-energized, energy within chemical batteries or capacitors of a BEV energy storage system can present a risk of electric shock and burns by high short-circuit current. Battery packs may require special procedures to bring down overall potential to an acceptable service value.

- Service areas on a vehicle should be designed to prevent unintentional contact with hazardous moving parts and voltages when adjusting or resetting controls or performing work similar that may be required to be performed while the BEV is energized.
- Conductors energized with hazardous voltages should be located behind protective covers that require a tool to access or remove.
- Warning labels should not be attached to removable protective covers.
- Service areas containing hazardous voltages after the BEV is turned off should self-discharge to a non-hazardous level within 10 seconds of the BEV being turned off.
- Service areas containing hazardous voltages after the BEV is turned off and take longer than 10 seconds to self-discharge, require a manual discharge procedure, or cannot be discharged to a non-hazardous voltage (e.g., batteries) should be labeled with a warning symbol and a notice of where to obtain appropriate maintenance procedures.
- Battery electric systems of 24 V and/or higher main system voltage should be identified.

8.11.4 BEV Decommissioning OEMs should ensure that energy systems and service components are designed and packaged to meet transportation regulations applicable to the regions from which they are shipped, as well as the region where they are intended to be sold. For guidance, see ST/SG/AC.10/11/Rev.5 (Section 38.3 therein) and ST/SG/AC.10/1/Rev.17 (Table 4). See Section 9.2.8 for additional guidance on BEV component handling at end-of-life.

9. ENERGY STORAGE SYSTEMS

9.1 Introduction

The rechargeable battery is central to BEV operation. The battery storage capacity (energy density) limits the range that the BEV can travel between charges (Section 5.2) and is thus is the main obstacle facing widespread commercial and mining BEV implementation. Rechargeable lead-acid batteries have changed little since their invention in the late 19th Century. In the past four decades, the drive for smaller, lighter, more efficient, less expensive, and more energy-dense storage systems has driven innovation in battery technologies. These needs are even more critical in mining applications, where BEVs are large, heavy, and have high energy demands.

At the most basic level, a battery is one or more energy (voltaic) cells containing a conductive electrolyte to facilitate the movement of ions from the negative terminal (anode) to the positive terminal (cathode), thereby creating an electrical current. For example, lead-acid batteries often contain six cells with metal plates immersed in a water / sulfuric acid solution (Table 6). Lead-acid batteries have long been used and continue to be used in conjunction with fossil fuel to power cars, boats, and other commercial vehicles.

Given the relatively high energy density of LIBs (Table 6), they are currently the most common choice for

Table 5. Names, topics, and jurisdictions of standards related to energy storage systems, listed in the order they are cited in this section. Full standard citations are listed in Section 13.

Recommended Industry Standard	Topic	Jurisdiction	Citation
E/ECE/324/Rev.2/Add.99/Rev.2	Safety requirements of vehicle electric power train	International	United Nations, 2013
ST/SG/AC.10/11/Rev.5	Criteria, test methods and procedures for classifying dangerous goods	International	United Nations, 2009
J2288_200806	Standardized test method to determine the expected life cycles of BEV battery modules	International	SAE International, 2008
UL 1642	Requirements to reduce the risk of and injury from fire or explosion when lithium batteries are used or removed from a product and discarded	USA	UL, 2012b
UL 2580	Evaluates the ability of the electrical energy storage assembly (e.g., battery packs and combination battery pack-electrochemical capacitor assemblies and the subassembly/modules that make up these assemblies for use in BEVs) to safely withstand simulated abuse conditions and prevents exposure of persons to hazards as a result of the abuse	USA	UL, 2013
CAN/CSA-E62660-1:15	Performance and life testing of rechargeable lithium-ion cells for propulsion of BEVs and hybrid electric vehicles	Canada	CSA Group, 2015a
CAN/CSA-E62660-2:15	Test procedures to observe the reliability and abuse behaviour of rechargeable lithium-ion cells for propulsion of BEVs and hybrid electric vehicles	Canada	CSA Group, 2015b
IEC 62133-2:2017	Requirements and tests for safe operation of portable sealed rechargeable lithium cells and LIBs containing non-acid electrolyte	International	International Electrotechnical Commission, 2017
IEC 61508:2010	Aspects to be considered when electrical/electronic/programmable electronic systems are used to carry out safety functions	International	International Electrotechnical Commission, 2010
IEC 62061:2005 (plus amendments)	Requirements and recommendations for the design, integration, and validation of safety-related electrical, electronic, and programmable electronic control systems for machines	International	International Electrotechnical Commission, 2015
M421-16	Minimum requirements for electrical work and electrical equipment operating / intended to operate at a mine	Canada	CSA Group, 2016b
US CFR Parts 100–177	United States Code of Federal Regulations on Transportation	USA	United States Office of the Federal Register, 2012
Canada TDG	Transportation of dangerous goods regulations	Canada	Transport Canada, 2016
IMDG 2014, 2016	International Maritime Dangerous Goods Code. IMDG 2014 in force as of January 2016; IMDG 2016 in force as of January 2018	International	International Maritime Organization, 2017
IATA Dangerous Goods Regulations	International Air Transport Association Dangerous Goods Regulations	International	International Air Transport Association, 2017
ISO 14990-1:2016	General safety requirements for electrical equipment and components incorporated into earth-moving machines as defined in ISO 6165:2012	International	International Organization for Standardization, 2016a
ISO 6165:2012	Terms and definitions and an identification structure for classifying earth-moving machinery	International	International Organization for Standardization, 2012a

BEV applications. The cathode in LIBs for commercial BEVs can comprise a metal oxide (nickel, cobalt, nickel-cobalt-aluminum, or nickel-manganese-cobalt), manganese spinel, or iron phosphate (Canis, 2013; Recharge, 2013). The cathode is separated from the graphite, carbon, or titanate anode by a porous polyethylene or polypropylene membrane. The electrolyte is a mixture of lithium salt and organic solvents in liquid or gel form.

The BMS is central to the safe and efficient operation of the battery. Under the control of a microprocessor, the BMS monitors the energy consumed by the BEV during operation, and the battery pack voltage, current, SOC, depth of discharge (DOD), and temperature, as well as individual cell voltages. As noted in Section 6.2.2.1, the BMS also varies the current being delivered to the battery during charging. Finally, the BMS redirects the energy produced during regenerative braking to the battery pack.

9.2 Functional Requirements

9.2.1 Accessibility and Service Only a skilled person (International Electrotechnical Commission, 2004) should perform maintenance and service on batteries. The OEM should provide a preventive maintenance program, including a checklist for inspection of battery system and any special repair procedures.

9.2.2 Thermal Management and Testing Within a battery, heat is generated by the current flow (the Joule effect); temperature management is the purview of the BMS, which monitors the mean battery pack temperature and temperatures of individual cells, as well as the intake and output coolant temperatures if coolant is used. A high-temperature condition typically results from an external heat source or the voltage and/or current being out of the operating range. Temperatures exceeding 80°C can positively feed back to cause thermal runaway—exothermic reactions at the graphite / electrolyte interface—which can ultimately lead to venting of hazardous and flammable gases, venting of flame, and potential explosion of the battery assembly. In addition to posing a safety risk (Section 9.3.2), elevated temperatures accelerate the degradation of capacity and power in LIBs, and can cause electrical imbalance among battery cells. Thermal management "presents a significant gap in the knowledge commercial manufacturers and developers need to design and fabricate safe, reliable battery systems" for BEVs (Bandhauer et al., 2011).

Active testing of LIB over-temperature functionality should follow E/ECE/324/Rev.2/Add.99/Rev.2 (Table 5) for the thermal shock and cycling test, and the over-temperature protection test. The ST/SG/AC.10/11/Rev.5 T.2 thermal test (Table 5) is similar to the thermal shock test within E/ECE/324/Rev.2/Add.99/Rev.2: the batteries are stored at 72°C for 6 hours and then at –40°C for 6 hours for 10 cycles. They must exhibit no leaking, venting, disassembly, rupture, or fire and voltage cannot fall to less than 90% of the original voltage.

Table 6. Energy density and voltages of various rechargeable battery types (https://en.wikipedia.org/wiki/Battery_(electricity); Bandhauer et al., 2011; Recharge, 2013)

Type	Energy Density (MJ/kg)	Voltage
Lead-acid	0.14	2.1
Nickel cadmium	0.14	1.2
Nickel metal-hydride	0.36	1.2
Nickel zinc	0.36	1.6
Lithium ion	0.31–0.61	2.3–4.0

9.2.3 Cycle Performance and Battery Life Battery system cycle performance is a key metric of battery life. Standard test procedures in J2288_200806 (Table 5) should be used to determine the expected service life—in cycles—of BEV battery modules. Testing battery systems under a standard procedure yields results that can be compared among systems in the same mine or among different mines. Underground and surface BEV operational profiles likely differ. Specific testing (e.g., DOD, SOC, operating temperature) may be performed to better understand battery life under specific conditions. Certain battery types are better suited to unique underground usage profiles that are not captured in J2288_200806 (Table 5). These conditions and usage profiles should be defined and additional testing procedures may be applied to the systems to better estimate battery system life. The following standards are relevant to design and testing of battery systems: E/ECE/324/Rev.2/Add.99/Rev.2, UL 1642, UL 2580, CAN/CSA-E62660-1:15, CAN/CSA-E62660-2:15, and IEC 62133-2:2017 (Table 5).

9.2.4 Fire Prevention / Suppression The battery should have a fire suppression system designed based on E/ECE/324/Rev.2/Add.99/Rev.2 (Table 5).

9.2.5 Automatic Shutdown Depending on the battery type, operating parameters such as temperature, current, voltage, and SOC need to be constantly monitored and maintained within certain values. For LIBs, exothermic reactions from over-charge and over-discharge can lead to thermal runaway and destabilize chemicals in the battery. The BMS will typically monitor these operating parameters across all battery cells and automatically shut down the battery system if they exceed allowable operating parameters by disconnecting the main battery contactors. The automatic shutdown of the system should be designed and tested to comply with IEC 61508:2010 and IEC 62061:2005 (Table 5).

9.2.6 System Enclosure Generally, ingress protection specifications for the battery system enclosure are supplied by the OEM. Accessibility could be open (i.e., via covers or lids with interlock functionality) or closed, so that only OEM personnel have authorization to open the enclosure (e.g., for battery maintenance or repair). Other battery system enclosure considerations include:

- Venting requirements based on energy storage chemistry
- Temperature monitoring
- Arduous underground mining conditions
- Mounting for shock and vibration
- Material for wet, corrosive environment
- Appropriate clearances from battery cells/packs
- Designated lifting points of energy storage modules

9.2.7 Storage The battery system or BEV OEM should fully define the storage conditions for battery packs or components of interest—any devices containing battery cells that can be damaged or become inoperable by the effects of long-term storage:

1. Storage temperature range, ideal storage temperature
2. Component life without periodic SOC / state of health check
3. Component life with periodic SOC / state of health check
4. Maintenance intervals and documented procedures
5. Equipment required to maintain the components during storage

The maximum number of batteries stored and storage procedures in a particular location should be confirmed with the local authority. Protection and isolation during storage should follow M421-16 (Table 5).

OEMs should supply documented procedures for handling damaged battery systems or system components. Potentially hazardous system components should be identified if separate from the system as a whole. Documents outline safe handling and storage practices for battery systems that have been physically damaged or subjected to high temperatures, flooding, or other forms of abuse. Procedures should provide instruction for the safe reduction of stored energy (discharging) and verification that the battery is in a safe state. Specialized equipment (pack discharge resistors) for preparing and handling damaged battery systems should be provided by the OEM.

9.2.8 End-of-Life Energy storage systems in BEVs have a limited life and will eventually wear out. Battery system component end-of-life should be fully defined by the OEM for individual system components or the battery system as a whole. When a BEV energy system reaches end-of-life, it should be properly decommissioned and disposed of in accordance with local laws. In some situations, the OEM may be able to rebuild the battery system and bring it back to specification. Regardless of the approach taken, before the battery system is transported, it will need to be properly packaged and labeled. Packaging and labeling requirements vary by geographic location so the battery system OEM should be contacted for detailed instructions.

However, even a worn-out battery system can supply significant amounts of energy. Additionally, batteries contain materials that may require special handling, recycling, or disposal methods based on local laws. Mine operators should never attempt to disassemble, dispose of, rebuild, or re-purpose a battery system without contacting the OEM for instructions. Components or systems at end-of-life disposal / recycling procedures should be supplied by OEMs.

Components containing hazardous materials should be properly labeled to avoid improper disposal. OEMs should label energy storage systems to alert to owners of the need for special packaging, transport and disposal procedures. The energy storage system labeling should also include OEM contact information.

9.3 Safety Requirements

9.3.1 Hazard Identification and Effects Hazard identification analyzes how batteries interact with their environment. For LIBs, the following hazard conditions are identified during charging, discharging (BEV operation), and storage:

1. Charging or discharging at low temperature
2. Over-voltage (over-charge)
3. Under-voltage (over-discharge)
4. Overloading (over-current)
5. Over-temperature
6. External short-circuit
7. Internal short circuit
8. External heating
9. Chemical reactions
10. Mechanical crush, shock, penetration, or rupture of a cell resulting in liquid or flammable / toxic gas release

The cumulative effects of electrical and chemical hazard conditions can lead to thermal runaway (Section 9.2.2).

Potential effects of these hazard conditions are gas release, heat release, fire, and corrosive electrolyte release.

These hazards are strongly linked to thermal runaway. Gas release can lead to elevated levels of carbon monoxide and dioxide, hydrogen gas, methane, ethane, ethylene, propylene, and hydrogen fluoride (Recharge, 2013). In addition, gases can combust at gas temperatures exceeding 350°C.

9.3.2 Hazard Condition Monitoring Temperature detection by the BMS must be adequate to identify dangerous temperatures in the battery pack—that is, there must be a sufficient number of temperature sensors next to battery cells. Sensor data are used to prevent hazard conditions 1–5 in Section 9.3.1 by notifying the BEV control unit to take corrective action and cause an alarm if battery temperature is out of safe operating range. Actions could be to request the BEV stop using the battery, control ambient heating or cooling, or as a last measure, open the battery contactors. Hazard condition 6 is prevented by fusing. Hazard conditions 6–9 are prevented by appropriate battery mechanical protection, usage, and handling.

9.3.3 Hazard Condition Prevention and Mitigation Hazard conditions during charge, discharge and storage can be prevented by avoiding exposing the batteries to heat / fire (e.g., welding on or near batteries) or electrical abuse (Recharge, 2013). Further, all LIBs must be fitted with a BMS that monitors the state of the battery and prevents the occurrence of hazard conditions. In the event of a hazard condition, mitigation measures are to reduce sensitivity, reduce the reaction (e.g., manage the fire, manage fume emissions), and break the reaction chain (e.g., neutralize corrosive electrolyte spills) (Recharge, 2013).

During battery swap-out, a combination of intrinsically safe connections (touch safe, fail safe and redundant systems) and procedures must ensure isolation of high potential cell groups down to a more acceptable energy level when true zero energy is not possible.

Battery maintenance procedures by a skilled person (International Electrotechnical Commission, 2004) should ensure proper isolation of high potential cell groups down to a more acceptable energy level when true zero energy is not possible. Access for battery maintenance should be limited through the use of labels and the requirement for tools. Welding on or near batteries should only be done after consultation with the OEM.

9.3.4 Transportation Packaging, labeling, and notification precautions must be taken when transporting batteries. The regulations that apply depend on the geographical region(s) among which batteries are being transported and battery chemistry. Regardless of the quantity of batteries or transportation method, the most recent versions of local transportation authorities should be consulted for guidance, as well as the OEM. Transportation regulations ST/SG/AC.10/11/Rev.5, US CFR Parts 100–177, Canada TDG, IMDG 2014, 2016, and IATA Dangerous Goods Regulations (Table 5) should be consulted before transporting batteries, battery systems, and BEVs and spare parts containing batteries.

Transportation of damaged batteries or suspect batteries may usually be transported similarly to known good batteries; additional precautions usually apply. Local regulations—including those listed above—may require special labeling and packaging of the battery or battery system to provide additional layers of protection. Regardless of how minimal the severity of damage to a battery or battery system, local transportation authorities and the OEM should be consulted for transportation guidance for damaged or suspect batteries or battery systems.

10. CHARGING SYSTEMS

10.1 Introduction

Charging systems are as essential as the battery itself: without the charger, the battery and the BEV are useless. Chargers for modern batteries are also complex. They can monitor the health of individual battery cells and report charge and battery conditions in real-time via WiFi connections. Given that chargers are an integral part of the BEV system—and are also expensive—the charging philosophy (Section 6) needs to be established and understood early in the design process and by all participants of the mine design team.

Charging mining BEVs presents challenges absent from the commercial BEV world. The equipment is much larger and heavier. Batteries on most mining BEVs require a much higher capacity. The mine environment is far more hostile, with rough roadways, temperature extremes, dust, vibration, and concussion from blasting. An element that the two environments share is a great variety in BEVs. A given mine will likely employ BEVs from several OEMs, each with different sizes, battery types, and usage profiles (e.g., Table 8). Thus, a major hurdle to overcome when introducing BEVs into a mine is a strategy for charging all BEVs. As noted in Section 6, a simple and standardized charging interface is key to making BEV charging simple, convenient, and safe.

Although OEMs would have their own packaging specifications and requirements, mine-specific packaging requirements would need to be communicated to the OEM to prevent damage to the charging system during transport to the mine. Once the charging system is delivered to the mine, constraints on transport (e.g., tipping, vibration shock, and fit within the mine conveyance system) need to be imposed. Before installation, standardized markings would need to be added to the charger to:

- Identify the device as a BEV charger
- Identify energy storage type / chemistry compatibility (see Section 10.5.2.3)
- Provide icon-based operating instructions (step 1, 2, 3, etc.)
- Indicate regional standards for installation and operation

The jurisdiction has a significant effect on the electrical and safety standards to which the BEV chargers—and indeed BEVs themselves—should be designed. In many locations, an electrical code is in effect. Typically, an "authority having jurisdiction" enforces the electrical code, often through a permitting and/or inspection process. Design and construction of the chargers should be such that they meet the appropriate electrical standards (Table 7). Further, the final installation of the chargers should respect the local practices, and undergo any approvals or inspections that may be necessary.

10.2 Safety Considerations

While working with the charging system and in or near the BEV, workers are exposed to electromagnetic (EM) radiation. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has several guidelines regarding magnetic field exposure (http://www.icnirp.org/). Based on commercial BEVs, health risks associated with direct EM radiation exposure appear to be low. Digital communication devices also emit EM radiation. As their use grows, it is increasingly important to limit EM emissions. Chargers should be compliant with regional EM emission and susceptibility standards (Table 7).

The charger-BEV interface is a point of interaction between the charging system and BEV operators, who are accustomed to diesel-based mining equipment. Safety features must be compliant with regional safety standards (Tables 7 and 8). Ergonomic functionality must be designed to prevent shock and mechanical hazards and avoid physical risk when workers install, connect, operate, disconnect, and maintain the (initially unfamiliar) charger system. Training programs are essential to safely operate the charging system, and avoid collisions and pedestrian interactions in the charging area—especially at busy times during a work shift. This section details safety features that should be universal among charging systems and safety features for specific charger types.

10.2.1 Installation The installation of the charger should comply with local codes. Further considerations for the charging station include:

- Adequate space for personnel to safely navigate and work on foot and in the BEV (e.g., turning radius)
- Level floors that can be easily cleaned (concrete if possible)
- Adequate visibility and lighting of battery charger controls

Table 7. Names, topics, and jurisdictions of standards related to chargers, listed in the order they are cited in this section. Full standard citations are listed in Section 13.

Recommended Industry Standard	Topic	Jurisdiction	Citation
IEEE-519-2014	Establishes goals for design of electrical systems that include both linear and nonlinear loads	International	Institute of Electrical and Electronics Engineers Standards Association, 2014
IEC 61851-23:2014	Requirements for the control of communication between the DC charger and the BEV	International	International Electrotechnical Commission, 2014c
DIN SPEC 70121	Specifies the DC-specific communication between the BEV and the electric vehicle supply equipment	Europe	Deutsches Institut für Normung e. V., 2014

Table 8. Example of fleet vehicles

Vehicle	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

- Compatibility with the type of charging system planned (i.e., fixed, cable connected / temporary, or fixed for operation but easily transported to other areas)

Key features should be considered for the charging area before installation:

- Ventilation/cooling system
- Clearly identified parking spaces for BEV or batteries (swap out) under charge
- Drainage system and sump to limit mud and water in the charging area, especially after washing down
- Overhead support of charging cable
- Protection of charge cable from abrasion
- Remote emergency off switch near the charger, outside potential hazard zone
- Upstream, overcurrent protection device to supply the charger
- Upstream, earth leakage / ground fault (GF) protection device (GF circuit interrupter)

10.2.2 Maintenance Maintenance should be performed according to OEM recommendations.

10.3 Environmental Range of Operation

As noted in Section 7, equipment and activities in the mine environment produce dust, water, localized heat, vibration, and percussion blasts. Depending on the mining level and mine location in terms of climate, the environment where the charging system is housed may be hot or cold. To maintain optimal operating temperatures, a cold weather package / internal heaters or cooling may be required. Today chargers with 150 kW and above are frequently liquid cooled. Alternative, an air conditioning unit could be mounted on the charger enclosure. If cooling is not sufficient, overheat protection on the charger should shut it down.

10.4 Incoming Power System

The power system in an underground mine often extends to great depths and distances, providing power for all underground loads—ventilation fans, dewatering pumps, and mobile equipment. These loads can be large and start and stop frequently during a day. As noted in Section 7.5.4.4, chargers produce undesirable harmonic frequencies that interfere with other devices and degrade the power quality. Harmonic frequencies in power systems cause heating of equipment and conductors. As a rule of thumb, the power system should provide a fault current that is approximate 20 times the FLA of the charger (Institute of Electrical and Electronics Engineers Standards Association, 2014). The impact of the ventilation and other contributors should be integrated into the harmonic study. See Section 7.5.4.4 for further details on power system design.

The power requirements for a specific charger will be specified by the charger OEM. In addition:

- Distribution equipment must be located within a distance that ensures system strength
- Chargers should comply with IEEE-519-2014 (Table 7): total harmonic contribution should be less < 5% at the plant point of common coupling
- Incoming short circuit rating / withstand
- Input power requirements: voltage, current, frequency, phases, grounding, and isolation
- Considerations should be made for voltage fluctuations and other typical mine power challenges in the mine grid

10.5 Charger Output Cable

A rugged armoured charger output cable should be selected. The cord set should be as short as possible and have sheathing or other protective measures. To prevent damage when the cable is not in use, a retraction system, control device, or hanger should be considered. The cord set should be easily replaceable, in case it is damaged or needs to be longer (i.e., use longer cord rather than adding extension).

10.5.1 AC Connection to On-Board Charger As noted in Section 6.1, the charger system is not a consideration for on-board charging from an AC supply (Figure 1) because the charger is on the BEV. The output cable chosen is specific to the local conventions of a given mine / jurisdiction. The AC feed could be via a "jumbo" cable connection or dedicated disconnect—as chosen by the customer of BEV OEM.

10.5.2 DC Connection to Off-Board Charger Off-board charging of either on-board or off-board batteries (Figures 3 and 4, respectively) locates the transformers and rectification equipment in a fixed enclosure removed from the BEV. All off-board charging in mines today is proprietary; the chargers are specifically designed for the BEV and supplied by the OEM (Section 6.2.3). The benefit is that all components come from one supplier, who bears the sole responsibility for performance. However, proprietary charging is infeasible for full-scale deployment of BEVs throughout an entire mine, because having a specific charger for every type of BEV is cumbersome. The mine design team should select a standard DC charging interface: every BEV and every DC charger in the mine should have the same type of connector and protocol. Connector and protocol options are described below and in more detail in Section 6.

10.5.2.1 Connectors The CHAdeMO or CCS Type 1 or Type 2 connectors (Section 6.2.2.1) have the following advantages:

- Proven performance in automotive industry
- Locking connector
- Relatively lightweight and manageable
- Testing of various scenarios comes "out of the box" (e.g., insertion / removal testing)

Disadvantages include:

- Automotive connectors are all plastic, which are often not rugged enough for mine duty
- CHAdeMO voltage (500 VDC) is not high enough for mining applications
- Uncertain whether ratings are acceptable for use in a mine
- No environmental protection

Overall, the application of off-board charging in mines is an evolving situation. Ultimately, multiple connectors may be required.

10.5.2.2 Protocol Option 1: PLC communications benefits:

- Leverage automotive "standard" chargers
- CAN/PLC interfaces are available for purchase
- Established communications framework with the BEV, whereas CAN is more wide open
- IEC 61851-23:2014 / DIN SPEC 70121 is now being chosen as industry standard in bus industry, as well as port equipment

Option 2: CAN using CHAdeMO or with custom communication framework benefits:

- Greater distance (probably not a big issue)
- More universal

10.5.2.3 Other It is important that the selected charger is compatible with the energy storage type and chemistry in use at the mine and is rated for the appropriate charging rate (slow or fast). If cooling is provided, ratings with and without cooling (chemistry related) need to be considered. Chargers should accommodate the different types of batteries in use, such as LIBs and molten salt batteries With DC charging (off-board) the vehicles' BMS is in "master" mode. Therefore a variety of chemistries can be charged, as long as the appropriate standards are implemented.

An output voltage range of 300–1,000 VDC is recommended. It is also recommended that the power electronics are separated from the operator interface. The power electronics should be installed in a dedicated charger electrical room. A decentralized human-machine interface should be installed at the charging area.

- Voltage drop may be an issue
- Another alternative is to move the charger around as needed—subject to the mining strategy in use

10.5.3 Hybrid As described in Section 6.4, a hybrid charging arrangements (Figure 9) offers a low-capacity AC charger that allows the batteries to be recharged over a relatively long time and an off-board rapid DC charger. Most commercial BEVs employ a hybrid arrangement.

10.6 Operation and Controls

10.6.1 Operator Control Visibility and Lighting When the charger is connected to the BEV, the BEV gives the charger instructions and minimum and maximum current limits. The charger complies and provides the requested current. Status indicators to the operator are:

- Normal operation
- Fault
- Charging in process
- Remaining charging time
- Charging complete

10.6.2 Emergency Shutdown Terminals An E-Stop button—connected to an automatic fire suppression system or manual systems (hoses and extinguishers)—should be provided outside the charger. The E-Stop button should be sequenced, so the power electronics shut down the charge first, followed by opening the contactors. If power electronics are not responding, then the contactors will dump. If the charger power "interface" is far from the charger unit, then an E-Stop is required at both locations.

10.7 Communications and Monitoring

The open charge point protocol (OCPP) enables BEVs to communicate (i.e., request and confirm) with a central system over the internet in extensible markup language (XML) format (Open Charge Alliance, 2016a). Within OCPP 1.5, the charge point initiates 10 operations:

1. Authorize
2. Boot notification
3. Data transfer
4. Diagnostics status notification
5. Firmware status notification
6. Heartbeat
7. Meter values
8. Start transaction
9. Status notification
10. Stop transaction

The central system initiates 15 operations:

1. Cancel reservation
2. Change availability
3. Change configuration
4. Clear cache
5. Data transfer
6. Get configuration
7. Get diagnostics
8. Get local list version
9. Remote start transaction
10. Remote stop transaction
11. Reserve now
12. Reset
13. Send local list
14. Unlock connector
15. Update firmware

OCPP 1.6 includes the following improvements over OCPP 1.5 (Open Charge Alliance, 2016b):

- Smart charging support for load balancing and use of charge profiles
- (Local) list management support
- Additional status
- Message sending requests such as charge point time or status at the charge point
- Minor improvements in specifications

Energy and charge management:

- Charge when power is cheap
- Don't charge everything at once (sequencing / demand management)

Desired features (both display on charger and recording/ supervisory control and data acquisition (known as SCADA) (provided from OCPP):

- Power usage: voltage, current, power, trending, peak
- Time of use/hours in use
- SOC (if possible, may be vehicle)
- State: alarms, status / temperature, connected / not connected

The BEV tag numbers and SOC should be transferred to the surface. The short-term mine planning should integrate this information to allow real-time intervals.

11. PERFORMANCE STANDARDS

11.1 Introduction

This section describes the type of data and information required to assess the capabilities of battery powered equipment for underground mines. The goal is to define the typical performance parameters used in the mining industry for underground mobile equipment, and to lay out example performance specifications and data sheets for the equipment, batteries, and chargers. The intent is to describe the performance requirements and capabilities to establish standard approaches for:

- Mine operators to specify the performance requirements to achieve their operational goals
- OEMs to describe the performance within the respective machine specification / data sheets, and communicate the information required from mining companies to ensure machines meet the operational goals

The mine operators will then be able to identify the availability of BEVs as potential alternatives to diesel equipment for their operations, and the OEMs will be able to ascertain the industry requirements.

11.2 Definitions

It is essential to ensure clarity on terminology used to describe the performance of the BEV in comparison to diesel equipment.

11.2.1 Duty Cycle

The overall performance of electric equipment should not be described in terms of the total time from the beginning to the end of a process as defined by the operator and the OEM, but should include both process time (i.e., when a unit is acted upon to bring it closer to an output) and delay time (i.e., when a unit of work is expended waiting to take the next action).

For BEV equipment, parameters and variables related to the duty cycle could vary. It is essential to capture the impact of delays and a key focus on action performance that is permuted by externals. Therefore, the duty cycle should be divided into actions that constitute equipment performance. Once the action performance has been evaluated without the influence of another machine, then permutations, combinations, and loops can be used to characterize the operation of a specific duty cycle. The duty cycle can be defined by primary actions for each class of equipment. Each primary action consists of at least one segment that defines energy consumed and grade, distance, and time traveled (Figure 17). These actions can be defined at fixed distance and/or tailored to specific mining applications. A cycle consists of:

- LOAD (MUCK)
- TRAM (HAUL)
- DUMP
- Return TRAM
- Repeat

For primary haulage equipment the duty cycle (also referred to as the muck cycle) is the production and development process for LHD machines (load-haul-dump, tramming loaded, tramming empty) and trucks (tramming loaded, discharging, tramming empty), as illustrated in Figures 18 and 19. For the LHD machine duty cycle of load-haul-dump or the truck box duty cycle of haul-discharge, an average energy consumption and time can be estimated.

For equipment, such as drills, bolters, and personnel carriers, a repetitive duty cycle may not be appropriate. Instead, the duty cycle would be defined by the time elapsed while travelling from one point to another under

Segment	Grade	Distance	Speed Limit
A-B	0%	20-50m	15 km/h
B-C	-15%	200m	5 km/h
C-D	-2%	70m	10 km/h

Location	Description
A	Working face
B-C	Haulage decline
D	crusher

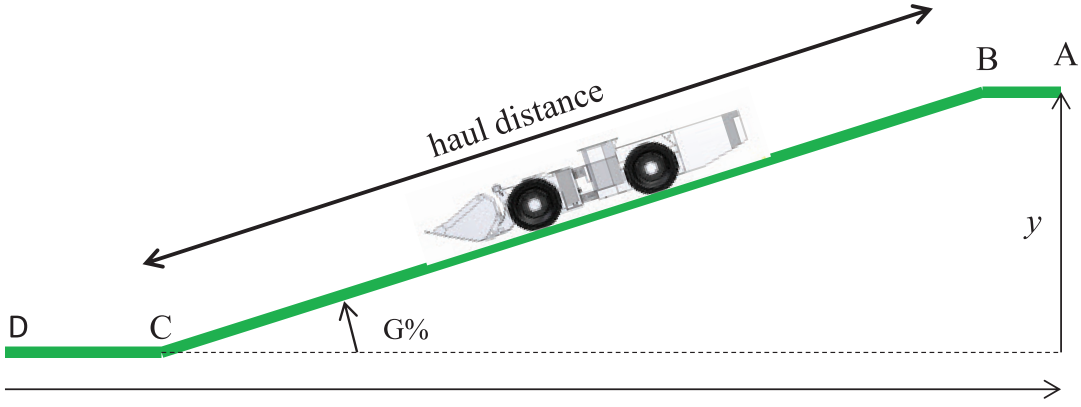


Figure 17. Primary Haulage Cycle

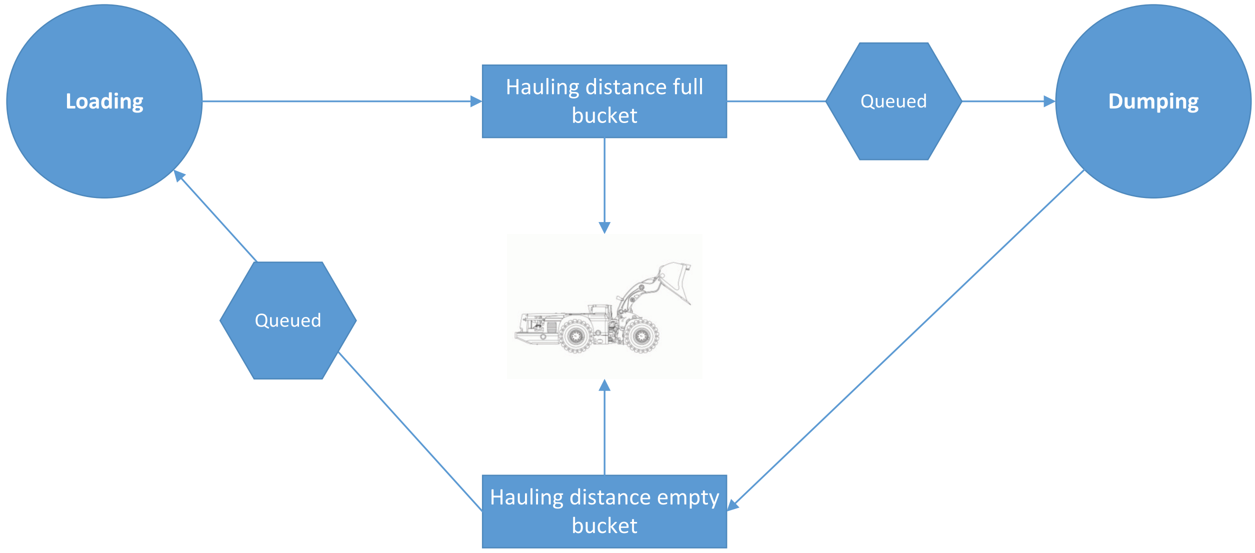


Figure 18. Short Distance Traveled Duty Cycle Scenario for LHD Machines and Trucks

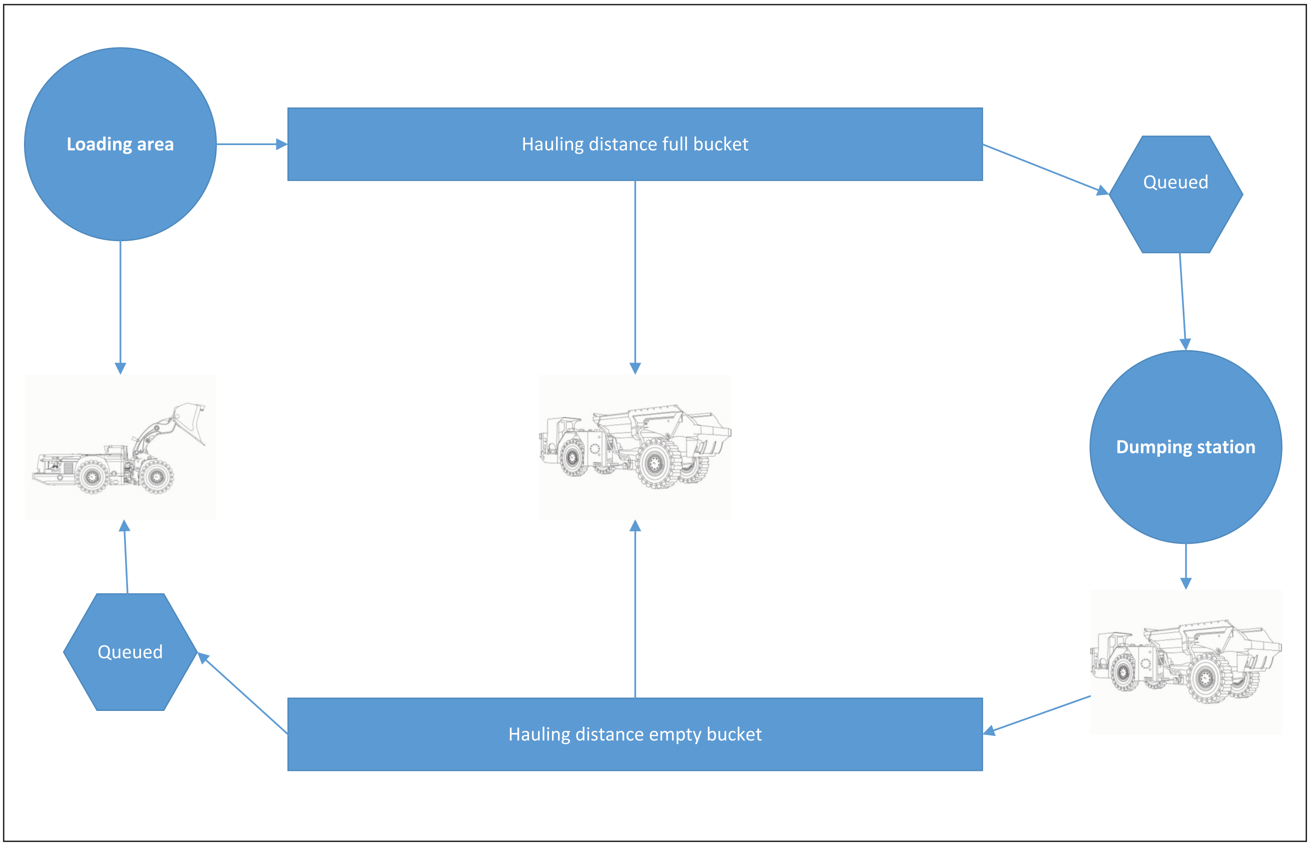


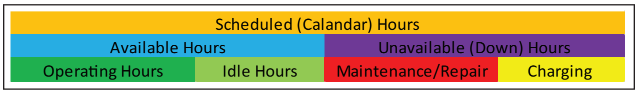
Figure 19. Long Distance Traveled Duty Cycle Scenario for LHD Machines and Trucks

various empty and loaded conditions. Usually, once it has arrived in the work area, this equipment is parked and shut off or plugged in to the grid.

11.2.2 Idle / Queued Periods Hypothetically, one duty cycle operates at 100% utilization. In reality, there are times when the vehicle is idle and/or waiting in line while consuming time and energy in a cycle and/or between sequences of cycles. These idle periods must be accounted for when estimating the actual performance in a fixed time period (e.g., 1 hour, 1 shift) as availability and utilization (Section 11.2.3).

11.2.3 Availability and Utilization Equipment availability is defined as the fraction of calendar hours without downtime for maintenance or repair. In the case of battery electric equipment, battery charging or swapping hours are considered maintenance hours where the equipment is not available for operation. Equipment utilization is defined as the percentage of time the available equipment worked.

Common definitions and formulas for the parameters are as follows (Figure 20):



Scheduled (Calandar) Hours

Available Hours | Unavailable (Down) Hours

Operating Hours | Idle Hours | Maintenance/Repair | Charging

Figure 20. Availability and Utilization Parameters for a Typical BEV

Scheduled hours = Calendar hours in a day, month, etc. (168 h/wk)
Available hours = Hours available to operate (includes any time between operating shifts)
Unavailable (Down) hours = Time unavailable due to breakdown, repair, battery charging, etc.
Operating hours = Hours operated as measured by hour meters on engine and/or motors

$$\text{Available hours} = \text{Scheduled hours} - \text{Down hours} \tag{1}$$

$$\text{Availability (\%)} = \frac{\text{Available hours}}{\text{Scheduled hours}} \times 100 \tag{2}$$

$$\text{Utilization (\%)} = \frac{\text{Operating hours}}{\text{Available hours}} \times 100 \tag{3}$$

11.2.4 Battery Charge Time The time required for on-board battery charging or battery swapping (off-board charging) can be significantly greater than for refueling comparable diesel equipment. If this time is significant, the machine is unavailable to do useful work and the time should be considered Down time. BEVs would then typically have lower availability compared to diesel equipment; the mine operator should take this into consideration when considering the application and reviewing OEM performance specifications.

Since Operating hours are determined based on hour meter data from the BEV motors (e.g., traction, hydraulic power pack, auxiliary) and the motors would be off during this charge time, these hours would not be recorded as Operating hours. However, it will be important for the mine operator to measure charging hours and add them to the recorded Down hours to truly see the impact on availability. Therefore, technology to record charging time—either on-board the machine or battery—should be considered in equipment specifications for BEVs.

11.3 Equipment Performance

11.3.1 General Requirements It is recommended that OEMs openly communicate BEV machine, battery, and charger performance metrics based on accurate in-field testing with standardized methodology and environmental parameters. This will permit mining operators to assess and compare the operational feasibility of the various OEMs' equipment. This process will reduce uncertainty and discrepancies in performance expectations. It is also recommended that OEMs provide the guidelines for the procedures and practices used to obtain performance measurements. The most significant performance requirements that need to be understood are:

1. The ability to achieve the same output for a given duty cycle as a comparable diesel unit
2. The energy requirements to perform the duty cycle, and number of such cycles capable by the battery energy stored on-board before recharge is required
3. The time required to recharge or swap the battery

To standardize and implement in-field performance protocols for BEVs, operational environmental variables and operational parameters should be considered and defined for the particular mining applications (Tables 10 and 11).

Also, OEMs should list all operating criteria / assumptions for the performance data communicated, including:

- Road conditions (e.g., rolling resistance assumptions)
- Ambient temperature
- Auxiliary systems operation (e.g., air conditioning / heating, lighting)
- Other battery loads (e.g., electric drives, controls, radios)
- Tire type and inflation pressure

11.3.2 Performance Standardized methods for describing performance for the traction, pump, and auxiliary motors are required to compare battery equipment to diesel

Table 9. Recommended charger monitoring frequency

Item	Frequency	Inspect for
Charger to vehicle coupler	Weekly	
Charger cord	Weekly	
Charger cabinet	Weekly	
Charger self-test	Monthly	
Safety interlock test		
Input voltage at terminal blocks	Annually	
Pin arcing	Annually	Damage
Charger OEM – test output	Annually	Full load test
GF functionality	Annually	Ground

Table 10. Examples of environmental variables

Parameter	Example Descriptors or Values
Road conditions	Firm, muddy, flexing slightly under load or undulating, maintained fairly regularly, watered, gravel
Rolling resistance	3%
Ambient temperature	Maximum 28°C wet bulb globe temperature in summer Underground temperature throughout the season varies on average between –5 and 45°C; exception will need to be addressed accordingly
Other considerations	Humidity Corrosion ratings Ingress protection ratings Salt resistance Rock falls

Table 11. Examples of operational parameters

Parameter	Example Descriptors or Values
Operator skills	At least 5 y experience
Idle periods	Any duration over 10 min. should be considered
Distance	In metres for each cycle
Payload	OEM would specify a payload and standard bucket volume, based on a specified rock (ore and/or waste) density
Charging station	Estimated time to reach charging station Estimated time to charge or swap
Grade	Uphill haul at 0–18% grade and specify distance Flat haul at 0–2% grade and specify distance Downhill haul at 0–18% grade and specify distance
Speed limit	Speed limit according to class of equipment
Specific remark	Tire type Inflation pressure

equipment. As an example, there is an arbitrary definition of peak vs. continuous ratings:

1. Peak rating in terms of diesel equipment is the maximum torque that could be generated at zero speed (i.e., stall condition while mucking) and that a torque converter at this operating point would survive for approximately 5–15 seconds before overheating. But that same drive train would be capable of running continuously loaded uphill at full power.
2. Continuous rating should characterize the average use of energy for an action; the peak rating often overestimates the value. However, the continuous rating may be a continuous uphill haul (same as diesel rating). Therefore the actions that drive continuous vs. peak and the frequency of such actions for peak should be clearly stated.

11.3.3 Regenerative Braking Systems There is an opportunity to use regenerative braking on BEVs (see also Section 7.2.2). When the speed pedal is released, the electric motor can become a generator and provide a braking force to the wheels while generating electricity to charge the battery. The amount of regenerative braking that is available can greatly influence range and must be clearly defined in the duty cycle.

If the battery is fully charged, regenerative braking may not take place unless there is an alternative dissipative component such as a brake resistor. Alternatively, the standard hydraulic brake could be called in to service when regeneration is not available. The OEM should provide details on the regenerative braking method, as well as the limiting factor for charging of batteries (e.g., 80%) to ensure regenerative braking could always be used.

11.3.4 Specifications The OEM should provide comprehensive specifications for the BEV that include performance information in a data sheet similar to Table 12. These data should be for typical power required at ideal conditions and at ambient temperatures as stated in the data sheets, in order to assist in understanding the efficiency of the OEMs battery electric drive system.

For basic grade performance data, a distance has not been not specified, and the units should be kW (power) at the maximum speed (km/h) attainable at that grade. In addition, typical duty cycle(s) should be described in as much detail as possible, and the OEM should use accurate simulation models to determine total energy required for each duty. The OEM should state if the data are measured or estimated and if estimated, specify the basis of the estimation and what verification testing would be undertaken prior to delivery.

11.4 Battery Performance

11.4.1 Performance A key performance criterion of interest to mine operators is the run-time of the equipment's battery (i.e., if the battery will last for an entire shift). Separating the overall BEV performance from the battery performance provides an understanding of the extent the latter improves with technology evolution.

Since the temperature of the underground working area where the BEV will be operating could affect battery performance, OEMs should provide the performance specifications based on a hot underground environment. However, this may not be practical. The OEM should indicate—at a minimum—if the proposed battery has been used in such environments and what measures need to be taken to alleviate the impact of heat. This is particularly important if there is no significant real mine experience.

By combining the consumed energy to perform specific tasks during worked hours in a shift and the battery capacity, the mine operator could estimate the run-time in terms of hours per shift. This information will assist in identifying the number of battery replacements or charges required

Table 12. Example of equipment performance data sheet

Performance Data

Power required at maximum speed (kW@km/h)
    0% grade (flat), loaded
    15% grade up, loaded
    15% grade down, loaded*
    0% grade (flat), unloaded
    15% grade up, unloaded
    15% grade down, unloaded*
    Zero speed with all auxiliary drives operating at maximum power
Loading
    Power (kW)
    Time (s)
    Energy (kWh)
    Breakout force (kg)
Dumping
    Power (kW)
    Time (s)
    Energy (kWh)
Range
    0% grade, flat (km)
    15% grade (km)
    No. trips on designated duty cycle: Run 1
    No. trips on designated duty cycle: Run 2
    No. trips on designated duty cycle: Run 3
    No. trips on designated duty cycle: Run 4
    Remaining battery on designated duty cycle: Run 5
    No. trips on designated duty cycle: Run 6
Effects of target environment (e.g., ambient temperature)

*Indicate portion regenerated for battery charging per shift per equipment, the dimensions and location of charging stations, the range of operations, and the mine infrastructure design and logistics. Parameters that define the battery performance should include those indicated in Table 13. Several metrics define the battery performance.

Table 13. Battery performance parameters

Parameter	Consideration
Voltage and current	Are there practical / safety limits that should be enforced? 1200 V IGBTs set ~800 V max DC link for example
Controllable charger	One fits all? Leverage bus standards?
Battery cycles	How to represent lifetime battery cycles? End-of-life definitions: • 70%? 80%? Secondary use • Rebuild? Replace? Repair? kWh nameplate – does not represent "useable" energy Beginning vs. end of life Warrantied kWh delivered?
Capacity	Number of cycles? Ah throughput? "Electric brake reserve" – how much battery needs to be reserved for downhill navigation? (Section 11.4.2)

11.4.2 Specifications Battery specifications are important to understand the BEV efficiency. The mine operator together with the OEM should define a set of useful parameters relevant to the operation. The OEM should then provide a battery performance data sheet similar to Table 14 and performance charts similar to examples listed in Table 15 and Figure 21.

11.5 Charger Performance

11.5.1 Performance From a vehicle performance standpoint, it is essential to specify the charging requirement so that it assists the mine operator or system integrator in the design of a suitable charging layout and vehicle operating schedule. It is important to understand the timing of charging, the location of charging stations, and potential opportunity for charging considerations based on mine power availability. The OEM should state the charging infrastructure requirements, indicating the number and location of charging stations and ventilation and electrical infrastructure requirements. If battery change-outs are required to meet normal operation requirements, then OEM should provide details of the excavation size and layout, as well as charging station infrastructure including lifting equipment and capacity requirements and fire suppression requirements.

11.5.2 Specifications An example of the basic charging system specification is given in Table 16.

Table 14. Example of battery performance data sheet

Description	Details (to be completed by OEM)
Cell	
Chemistry	
Specific energy (kWh/kg)	
Energy density (KWh/m^3)	
Nominal voltage (V)	
Amperage (A)	
Operating voltage (min–max V)	
Cell monitoring system	
Battery	
Nameplate capacity (Ah) total / useable	
Nameplate power (kWh) total / useable	
Number of cells	
Optimal discharge rate (e.g., 0.5C)	
Optimal charging rate (e.g., 0.5C)	
Maximum charge current (80% SOC)	
Operating temperature range (°C)	
Lifespan cycles at % DOD	
Self-discharge rate (%/monthly)	
Memory effect (Y/N)	
Cooling time (hours)	
Cooling method, if applicable	
Battery monitoring system	
Battery swapping (Y/N, time)	
Opportunity charging (Y/N, time)	
Battery pack weight (kg)	
Battery pack dimensions (mm)	
Charging time (lowest SOC 100%)	
kW of heat output per kWh of charging	
Gassing (if applicable)	

Table 15. Battery performance charts (example list)

Voltage (V) function of discharge capacity (%) at –45, –25, 0, 25, and 55°C
Voltage (V) function of discharge capacity (%) at normal temperature (21°C): 0.5, 1, and 2CA
Voltage (V) function of charge capacity (%) at normal temperature (21°C): 0.5, 1, and 2CA
Discharge capacity (%) function of time (days) storage under normal temperature (21°C)
Lifespan (cycles) function of DOD (%) at normal temperature (21°C): 0.5, 1, and 2CA
Lifespan (cycles) function of DOD (%) at: –45, –25, 0, 25, and 55°C

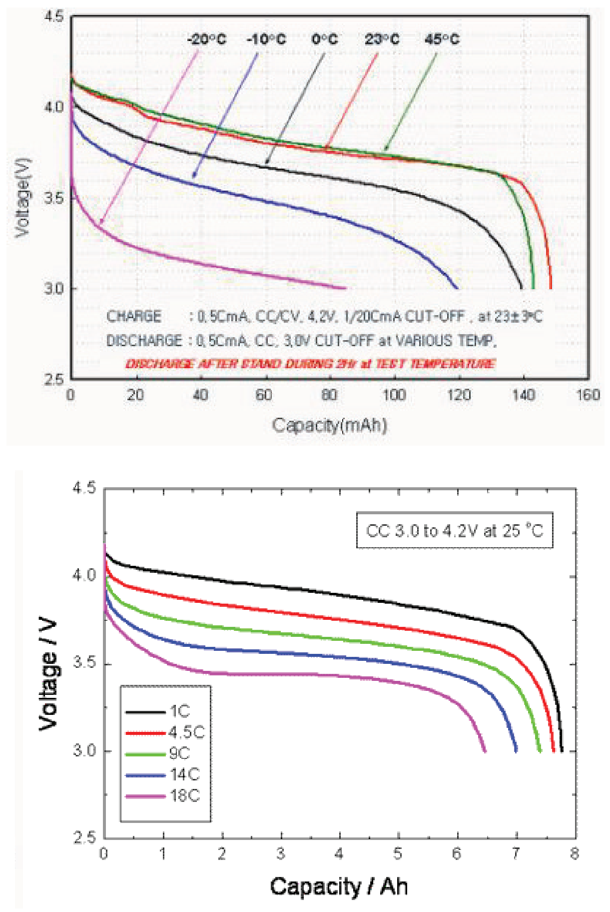


Figure 21. Examples of Battery Performance Charts

11.6 General Performance Requirements

The above specifications and data sheets will provide a useful summary of the features of the BEVs, but the various parameters on their own may make it difficult for the mine operator to conclude if a potential BEV solution would meet the overall production or service requirements at a specific mine location and application. Since these overall performance requirements are most important, the OEM should be able to clearly indicate if a particular equipment design can ultimately meet the requirements. An example of how this can be summarized is given in Table 17.

Table 16. Battery charger requirements

Description	Details (to be completed by OEM)
Dimensions (L × W × H)	
Weight (kg)	
Operating temperature (°C) and humidity	
Input range (max rated input voltage, current, power, frequency, VA ranges)	
Output range (i.e., voltage, current rating as well reference to fast / slow / regular charging rate)	
Power factor	
Charger efficiency	
Enclosure specifications	
Charge time (based on minimum SOC)	
Derating of charger capacity (if applicable)	
Heat rejection of battery charger over voltage and charging current range	

Table 17. General performance requirements (example)

Description	Details by Mining Company
Equipment	Battery-powered 30T truck hauling load up 15% ramp, 2.2 km
Objective	Haul 400 tonnes/shift
Description	**Examples of Outputs by OEM**
Energy (kWh/cycle)	10
Duty (loads/charge)	25
Duty (tonnes/charge)	750
Output (tonnes/shift)	400: objective met with no swaps or 326: possible with one swap
Production objective	Met in 1.2 h with no swaps or met in 1.4 h with one swap
Cycle time (minutes)	5.5
Speed (km/h)	10.5 loaded, 16 unloaded

12. FURTHER WORK

The technology related to BEVs in underground mines is advancing rapidly, as is the experience gained by the people and companies implementing it. Whereas this guideline presents the recommended best practices at the time of writing, new developments in technology and experience will soon supersede some of the recommendations. For this reason, GMSG welcomes suggestions for changes, corrections, recommendations for new material, or any other feedback. Please get in touch with us using the contact information found on page ii. All suggestions and feedback will be collected in preparation for the next edition of the guideline.

By early 2018, a working group will be formed to begin working on the next edition. As part of that group's mandate, they will review the guideline to determine if any elements of the guideline should be adopted into an international standard. If the conclusion is yes, they will identify the appropriate standards agency to work with, and pass those materials and the recommendation to them.

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