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GMG RECOMMENDED PRACTICES FOR BATTERY ELECTRIC VEHICLES IN UNDERGROUND MINING –

2nd Edition

SUBMITTED BY
Battery Electric Vehicles Underground Sub-Committee
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TABLE OF CONTENTS

1. FOREWORD

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

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

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This 2nd edition of the Recommended Practices for Battery Electric Vehicles in Underground Mining replaces the 1st edition, published April 28, 2017. This revised edition contains new material and the organization has been improved. To eliminate redundancy, the Charging Philosophy section has been removed, and the content has been divided between the Mine Design section and the Charging Systems section. Additions were made to the Mine Design, BEV Design, and Performance Standards sections based on experience gained since the 1st edition was published. Additions to the Energy Storage Systems and Charging Systems sections are based on new technologies that have been implemented. Finally, an Operations section was added to give direct advice to companies implementing BEV technologies in their mines.

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
CAN	Controller Area Network
CCS	Combined Charging System
CP	Control Pilot
CWO	Charge While Operating
DC	Direct Current
DOD	Depth of Discharge
DPM	Diesel Particulate Matter
EM	Electromagnetic
E-Stop	Emergency Stop
FLA	Full Load Amperage
GF	Ground Fault
GHG	Greenhouse Gas
HV	High-Voltage
HVIL	Hazardous Voltage Interlock Loop
LHD	Load Haul Dump (machine)
LIB	Lithium-Ion Battery
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OWHS	Ore / Waste Handling System
PE	Protective Earth
PLC	Powerline Communication
RR	Rolling Resistance
SIL	Safety Integrity Level
SOC	State of Charge
VAC	Variable Alternating Current
VDC	Variable Direct Current
XML	Extensible Markup Language

* See International Electrotechnical Commission (2004)

3. KEYWORDS

Battery electric vehicle, Charging, Connection interface, Electric mine, Mine design

4. SCOPE

This guideline outlines the recommended practice for use of battery electric vehicles (BEVs) in the 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 aims to strike an appropriate balance between standardization and innovation. It should allow miners to operate a fleet of BEVs without concerns about proprietary equipment and interfaces. It leverages and references existing standards and guidelines, including from applicable automotive, electrical, automation, and other industries. At the same time, the BEV guideline should not be an impediment to innovation for OEMs.

The BEV guideline is structured around seven key components, arranged in a logical sequence for an underground operation considering "going electric". At the conceptual stage, it is necessary to understand the basics of BEVs and how to build a business case for them. Work can then proceed from mine design, through to BEV design, energy storage systems (batteries), charging systems, operations considerations, and performance standards. Finally, because it is global in scope, mining companies and OEMs throughout the world should be able to use this guideline.

However, they should acknowledge that regional differences exist in terms of local 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 (GHG) 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 are more expensive than gasoline- or diesel-powered cars and require fixed charging infrastructure. Battery electric commercial trucks, buses, cars, and trains are generally far more efficient than their internal combustion engine counterparts. As an additional benefit, they can further increase efficiency by using regenerative braking (a type of dynamic braking) to convert kinetic energy into potential energy, which can then be re-used when accelerating later (for more details, see Sections 6.2.2, 7.3, and 11.3.3).

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

- Potential to dramatically reduce required air volumes compared to diesel equipment fleets
- Potential to reduce refrigeration loads associated with a reduced ventilation in deep hot mines
- Improved working environment in mine headings (i.e., no diesel particulate matter [DPM] and combustion gas emissions, reduced noise levels, less heat)
- Decrease in GHG emissions and operating costs
- Significant reduction in heat generation
- Potential to increase production with simultaneous BEV usage in mines with ventilation-constrained areas
- 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 and Disadvantages of BEVs vs. 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 DPM 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, emit fewer GHG and other gaseous and liquid pollutants (e.g., oil, transmission and radiator fluid), and emit no DPM. Thus, the work environment is cleaner, even along haulage routes. Several technical papers have been published describing the efficiency benefits of battery electric drives over internal combustion engines. For example, depending on the application, the portion of energy transferred to the wheels can be up to five times greater (Center for Energy, Transportation and the Environment, 2018). Unlike diesel engines, BEV engines do not idle when the vehicle is parked, which means energy consumption and heat output are lower. Since virgin rock temperatures can reach 80°C (Fiscor, 2014), BEVs may be the preferred choice for mines that must exploit deeper resources, where cooling and ventilation costs would otherwise make the project infeasible. Further, BEVs are broadly perceived as socially acceptable (Hanke, Hülsmann, & Fornahl, 2014).

High energy content is the greatest benefit of fossil fuels over electric. The specific energy density (energy per unit mass) refers to the capacity to store energy, thus it determines a vehicle's range and capacity to do useful work. The specific energy of diesel is nearly 50 MJ/kg—more than 55 times higher than the most energy-dense LIB (0.900 MJ/kg). The volumetric energy density of diesel is approximately 35 MJ/L—nearly six times higher than the most energy-dense LIB (6.2 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, Wolverton, & Isaacs, 2012).

The higher energy content of diesel is somewhat offset by lower efficiency of use: a large portion of the energy content is lost as heat during diesel combustion. 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, do not idle at rest, and there are reduced 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 more complicated. In addition, the BEV market is still in its infancy and methods to deliver a charge are not yet standardized across the industry.

5.2 Business Case

All-electric mines offer distinct advantages compared to conventional mines, especially in reducing diesel emissions and associated negative impacts on worker health (see Section 5.1). Development and mining of some orebodies may never be profitable unless zero-emission BEV use is permitted, due to the ventilation requirements of diesel vehicles. However, compared to conventional mines, all-electric mines offer a host of challenges that must be considered when evaluating a project. These challenges may impact the business case from revenue, capital cost, and operating cost perspectives. When reviewing these categories, the following factors should be considered as they will vary between mines and are applicable to both greenfield or brownfield implementation:

1. Revenue increase
    - Productivity gains due to improved air quality
    - Productivity gains due to cooler work environment (particularly related to work / rest regimes in hot work environments)
    - Earlier revenue profile due to faster regulatory approval for BEVs
    - Potential to mine traditionally uneconomic orebodies
2. Capital cost impacts
    - Additional capital expenditures required for battery-related infrastructure such as charging areas and accompanying infrastructure to control charging related heat
    - Reduced cost associated with the diesel fuel handling system
    - Additional capital expenditures for BEVs and associated batteries
    - Reduced ventilation-related capital due to reduction in overall volume requirements in both the main system and the auxiliary system
    - If applicable, a reduced cooling-related capital due to the reduction in heat generated
    - All other mine design related changes impacted by the introduction of BEVs, such as quantity and size of drifts and shafts
    - Potential for government subsidies or grants for using green technologies
3. Operating cost impacts:
    - Reduction in energy requirements and costs of diesel and electricity due to the higher efficiency of BEVs relative to diesel counterparts
    - Reduction in ventilation-related operating costs due to smaller overall systems
    - Elimination of diesel fuel transportation systems and the related logistics costs
    - Reduction in mobile equipment maintenance costs

5.2.1 BEV Benefits to the Business Case

1. Health, Safety and Environment: An important benefit of BEV use in underground mines is general improvement in the working environment (i.e., less noise and vibration from electric drives) and worker productivity (see Section 5.1). Health risks to underground workers from diesel emissions are totally eliminated by electric drive machines. Reduced heat, particularly in warm climates and in deep mines, can lower the need to implement work / rest regimes.

2. Energy: One litre of diesel fuel converts to approximately 3 kWh of useful energy, a ratio of 1 kWh of electrical power to 1/3 diesel price per litre, excluding ventilation costs. The energy potential of diesel is greatly reduced once internal combustion engine losses are factored in (e.g., idling time, transmission losses, other auxiliary system losses). With BEVs, a far greater percentage of the energy purchased is converted to power at the BEV wheels.

3. Ventilation: Eliminating harmful diesel emissions substantially reduces mine ventilation requirements. From a capital expenditure point of view, this means smaller and potentially fewer ventilation shafts, smaller access drifts, and smaller fans. Savings are substantial when combined with operational savings in electricity costs, given the affinity curves of ventilation fans. Depending on the local climate, a lower air flow rate could yield savings in winter heating costs.

4. Heat Generation: Less heat is generated from the ventilation system (autocompression and fan input power) and from electric engines. Overall, this translates into smaller (or even no) refrigeration equipment and lower electrical operating costs.

5. Maintenance: Maintenance costs are generally less for electric than diesel engines, primarily because of the high reliability of the electric motor and the static nature of the electric drive and controllers for the motor. Furthermore, a well-designed electrical drive system incorporates a vast array of interconnected sensors to monitor and warn the operator of faults, as well as provide trending data for the predictive maintenance system.

6. Equipment Performance: The power rating of diesel haulage equipment is limited by ventilation constraints. This constraint doesn't exist for BEVs. Thus, for units with similar payload capacity, larger electric drives can be applied, resulting in improved equipment performance (i.e., breakout / lifting capacity, acceleration, and speed). However, performance enhancement may be somewhat offset by the time lost to recharge or swap batteries and a possible loss in overall productivity if charge time is not accounted for in the operation.

5.2.2 BEV Challenges to the Business Case

1. Modelling energy consumption: BEV performance affects the entire cost model and must be measured accurately. From the quality of the paving, to the capital cost per BEV, to the quantity of chargers, performance-related factors are interconnected in various ways that present multiple trade-offs.

2. Energy density: To improve operational efficiencies and lower production costs, mines need to move ore as quickly as possible with the lowest interruption rate. The low energy density of a battery relative to diesel (see Section 5.1) must be modelled in advance to ensure the charging philosophy (Section 6.5.2) will work in unison with the mine plan.

3. Operational changes: The need to swap or charge batteries multiple times per day may affect BEV availability; this challenge should be reduced by development of new technologies. In addition, workers who currently work with diesel equipment will need to be trained to operate and maintain BEVs.

4. Disposal of old batteries: Battery disposal is an issue that must be addressed (see Section 8.2.9). When batteries are no longer suitable for use in BEVs, they can find a new life as energy storage for utilities or for the mine; however, they will ultimately need to be recycled. One option to address this challenge is to rent batteries from the BEV OEM.

5.2.3 Capital Cost Considerations

1. Vehicles: The cost of a BEV is currently higher than a diesel equivalent, largely driven by battery costs.

2. Electrical infrastructure: Battery chargers can be a 100% duty cycle load while charging and nearly 0% while not charging. These step loads can create demand peaks on the electrical system that must be reviewed and assessed hourly to properly size the electrical system. The cost implications could be significant, depending on the charging philosophy adopted (Section 6.5.2). In addition to the electrical distribution system, a complete system of chargers needs to be implemented within the mine, which comes at a significant cost. The mine may have one charger associated with each piece of equipment, or one charger for multiple pieces of equipment. These chargers become localized heat sources that require additional ventilation.

6. MINE DESIGN

6.1 Introduction

Lower ventilation requirements are the primary drivers for changes to the mine design to accommodate mine electrification—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 vehicles and BEVs), additional infrastructure will be required throughout the mine to maintain and operate the BEV fleet.

The first considerations relate to charging method (see Section 6.5.2):

1. Appropriate infrastructure (e.g., excavations and electrical systems) for on-board charging, off-board charging, or battery swapping
2. Mining cycle and schedules for charge time vs. operating time
3. Power regeneration opportunities
4. Cost implications of charging methods

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

1. Charging stations at dedicated locations
    - Shared chargers
    - One size fits all
    - Specific chargers match specific equipment
    - Footprint of the power source for the charger and charger itself, room to park a BEV and leave it aside to charge
2. Battery maintenance shop / facilities / equipment
    - Effective communication between underground and OEM
    - Dedicated maintenance battery charger(s)
    - Spare batteries and chargers
3. 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
4. Mechanical / electrical garage and spare parts storage
    - 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, changing tires, drive train work (if applicable), hydraulic system maintenance and electric maintenance (motor, battery, computer, and charger), and additional service on secondary equipment
    - BEVs have few moving parts, thus require less equipment storage
    - BEVs have specific requirements for spare parts, which should be reviewed with the OEM to ensure sufficient real-estate is reserved

6.2 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. When transitioning to mining BEVs, it is essential to reconsider the traditional methods of mine development. The many advantages of transitioning to mining BEVs are described in Section 5.1. Nonetheless, BEVs have several limitations relative to traditional diesel equipment, the most important being the limited range and the time needed to charge. The key to a 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.

6.2.1 Ore / Waste Handling System (OWHS)

Whereas ventilation / cooling systems will benefit the most by the implementation of an electric fleet (e.g., air quality, humidity, noise, and maintenance), the OWHS has the greatest chance of being affected. It consumes large amounts of energy and thus 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. Thus, this section focuses on the impact of electrification, not OWHS design or current methods (e.g., diesel equipment, conveyors, or train cars). Understanding BEV operation is crucial to optimizing 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 6.2.2, 7.3, 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 battery management system (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 1 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 6.4.1 and 11.2.1).

6.2.1.1 Trolley assist systems Trolley assist systems collect electricity from overhead conductors for use by electric motors. Adoption is limited by:

- High capital and maintenance costs

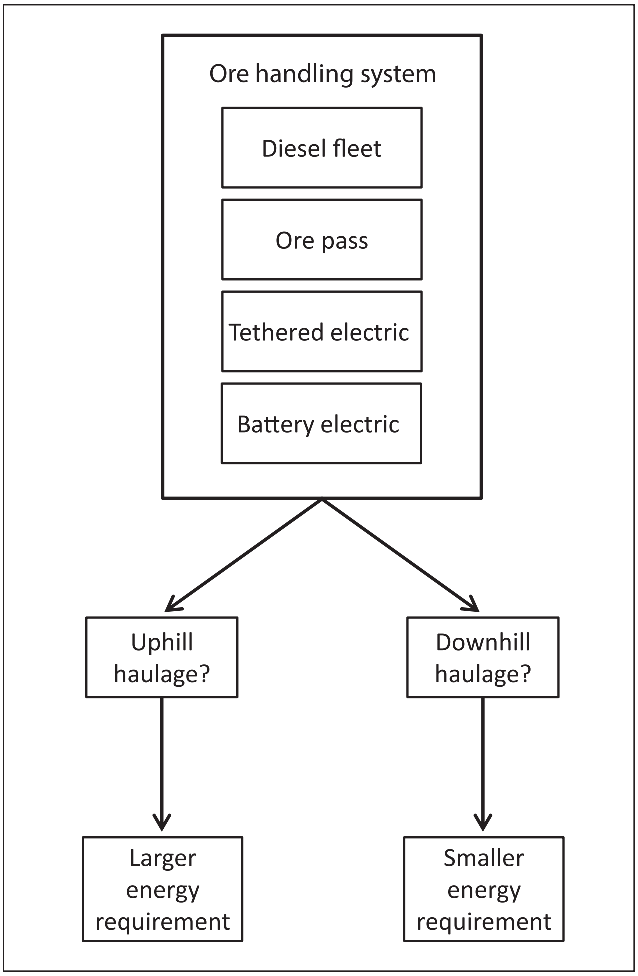


Figure 1. Impact of Ore / Waste Handling System on Battery Sizing

- 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

Trolley assist trucks are currently fitted with small diesel engines that allow for short horizontal movements while disconnected from the trolley. There is potential to design a hybrid trolley–battery truck with battery-powered motors that would allow longer trams while disconnected. 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 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.

Existing trolley truck systems require high upfront capital, not only for the trucks themselves, but for the engineered roadbeds and the associated electric trolley systems. A typical roadbed consists of 0.5 m depth of aggregate material topped with granular 'A' with a liquid asphalt emulsion. The capital cost of these high quality roadbeds can be high, but they allow trucks to travel at speeds in excess of 20 km/h. Regular maintenance consists of removing fallen ore chunks using a grader and load haul dump (LHD) machine, removing road dust using a sweeper / vacuum mobile vehicle, and applying asphalt emulsion to the walls to combat accumulating dust. The trolleys also require regular maintenance, typically to combat metal fatigue.

6.2.2 Regenerative Braking

Compared to diesel, the energy density of batteries is by far the greatest limitation to be overcome for widespread BEV adoption (Section 5.1). However, the regenerative capabilities of electric motors can potentially lessen the magnitude of this problem (Sections 7.3 and 11.3.3). With a diesel vehicle, friction braking converts kinetic energy into heat. When braking a BEV, the motors push most of the kinetic energy into the on-board batteries, with the following advantages:

1. Longer BEV range
2. Lower energy consumption (higher efficiency)
3. Batteries may be sized smaller
4. Less heat is introduced into 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 6.2.1). 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 1). 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.

6.2.2.1 Straight vs. curved ramps

Mine developments targeted for BEV use could follow one of two design principles to keep the net overall ramp within prescribed geographic bounds:

1. Series of long straight inclines with a nominal 180° or less return curve
2. Traditional constant radius spiral ramp design

Both designs achieve the same vertical travel displacement and travel distance and utilize the same grade; therefore, they excavate similar volumes of material.

However, differences could arise in terms of drive efficiency. When vehicles drive through corners, the forces imparted through the tires to maintain the intended path (i.e., to overcome centrifugal force) cause several related force events to occur. Foremost is the force required to move the vehicle forward. Added to this is the force required to move the vehicle in the direction of the turn and the associated drag from the tires now attempting to slip (vs. free roll) on the roadbed. The force of the tires attempting to slip can be visualized by the displacement of roadbed material towards the outer radius of the corner. These additional forces in the machine mechanism increase internal friction and wear. The action of turning the corner activates differentials and causes related changes in motor speeds, all factors that affect efficiency. These factors may be minimal in some cases and significant in others. Testing should be conducted to confirm the magnitude of these forces and determine which design principle should be employed.

6.2.2.2 Ramp grade Stored energy on a machine is used to change the energy state of the machine or the environment. In a BEV, chemical energy in the battery produces voltage and current, which is used to rotate a motor, which in turn drives wheels to move the machine. On flat ground, the mechanical power from the wheels puts energy into the kinetic energy of the machine. On a ramp, there is a change in the potential energy of the machine and load. When going down ramp, the potential energy is driving the wheels and the system is able to recoup some portion of the energy and return it to the battery. When driving up ramp, battery energy is used to raise the potential energy state of the vehicle and load. Ramp angle affects the power going to and from potential energy.

To find the most efficient speed and ramp angle, three types of losses must be considered:

1. Continuous (steady state)
2. First order or speed dependent (friction)
3. Second order or viscous

Vehicle speed affects friction loss in a linear fashion, and the viscous losses increase with the square of the velocity. For slow moving equipment with low rpm motors and drivelines, losses will be more friction based; it is likely that higher speeds of travel will be more efficient up to the point that the resistance of conductors in the system become a large component in the total losses. Often these losses are the basis of the power limits of the motors, drives and batteries. If the equipment is traveling too slowly, more energy goes to steady state losses but less energy goes to viscous losses.

For a BEV, traveling too quickly increases friction and viscous losses. There are also limitations on the amount of power a machine is capable of producing and accepting. These limitations limit the speed of travel.

Mathematical models that take into account all losses and accurately predict the effects of speed and power draw are necessary to determine the optimal operating case. The models should be tested and proven in the field and the information included in BEV specifications. A curve derived from one such model is demonstrated in Figure 2, which shows the trade-off between increased steady state losses due to a longer haulage distance for the same elevation gain and diminishing return in energy savings as ramp angle increases. Increased ramp angle shortens the haulage distance and decreases the travel time, but increases the torque and power load on the machine, thus increasing the losses with the square of the ramp angle increase. Note that the model used for this curve did not account for loss of traction at higher ramp grades.

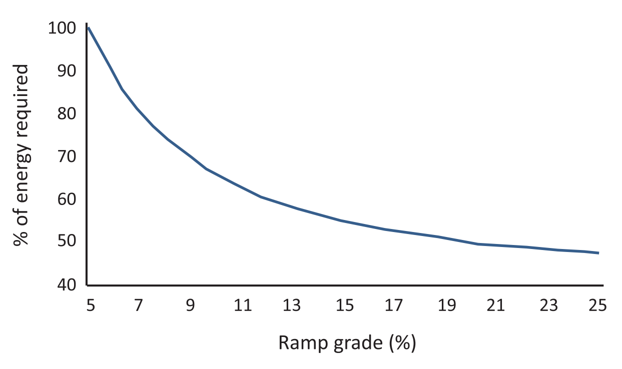


Figure 2. Energy Required for Fixed Elevation Gain at Fixed Speeds

6.2.3 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 provide suitable parking locations. The most significant problems might be logistical issues or conflicts among crews over vehicle parking. However, in 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 facilitate 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.

6.3 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.

6.3.1 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 6.5.4 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
    - BEVs are parked close enough to shaft stations for personnel to walk to / from a BEV
    - Requires sufficient parking locations and charger for all BEVs and sufficient power to supply chargers
    - Likely not feasible for certain pieces of mining equipment (e.g., bolters and jumbos)
2. Personnel carriers
    - Located near the shaft station to transport personnel to locations in the mine
    - Can bring workers to parking locations
    - Can bring workers to mining levels to reach mining equipment
    - Consider charging personnel carriers near work areas once all personnel are delivered
3. Combination
    - 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
    - Slow movers or equipment typically dedicated to the mining zone (e.g., bolters and jumbos) are left in or near headings; workers are transported to them via personnel carriers

6.3.2 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 transport personnel in and out of the mine in dedicated group transportation BEVs; 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 3 illustrates the personnel transport options that affect battery size requirements of a BEV.

6.4 Other Electric Equipment

Each type of electric equipment has a different charging configuration, as illustrated and summarized in Figure 4.

6.4.1 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 charg-

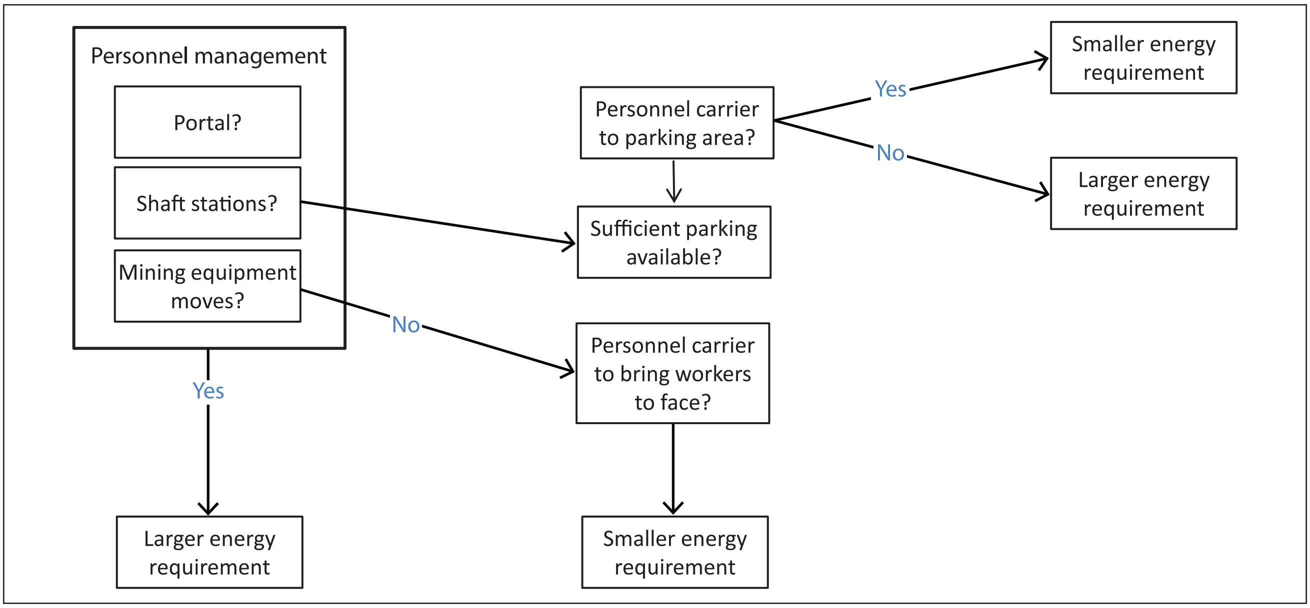


Figure 3. Simplified Personnel Management Impact on Battery Sizing

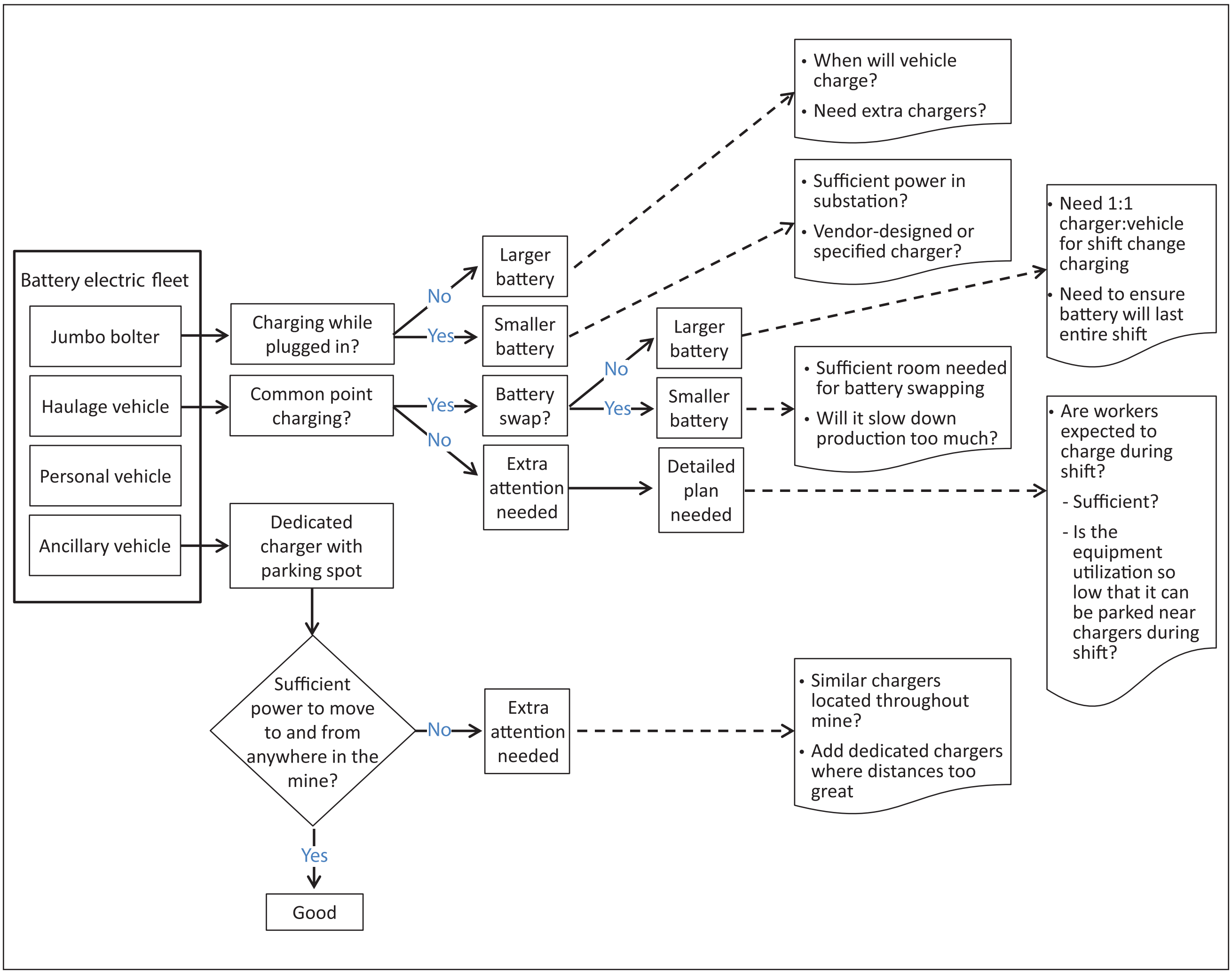


Figure 4. Electric Fleet Design Considerations

ers required on each mining level (Section 11.2.1). This exercise makes it apparent that off-board charging is 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.

6.4.2 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

6.4.3 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

6.4.4 Alternate Haulage Methods

Alternate haulage methods include conveyors, electric-powered trains, trolleys, and monorails, railed conveyor, and continuous haulage systems.

6.4.5 Auxiliary Vehicles

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

6.5 Charging Infrastructure

Once personnel transport needs are determined, the equipment is chosen, and the mine is generally laid out, the charging infrastructure can be defined. A BEV charging system typically consists of a step-down and isolation transformer, a rectification system / variable direct current (DC) supply, and a charge rate controller. Mine operations will depend on the availability of fully charged batteries; therefore, sufficient design in the charging system is crucial. The charging philosophy (Section 6.5.2) and factors depicted in Figure 5 will influence the mine layout and must be considered.

6.5.1 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 required throughout the mine and their locations
- Whether opportunity charging will be employed (Section 6.5.4)
- Preference for each piece of equipment: battery charging in-shift, at end-of-shift, or through battery swapping
- 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, for example, a grader that cannot reach all areas of 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.

6.5.2 Charging Philosophy

A successful electric mine design begins with understanding and harnessing the benefits of BEVs, while accounting for the shortcomings. 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.

The starting point should be the mine layout and the operational map of the vehicles. Since electrical infrastructure is spread throughout the mine, chargers can be easily added as needed. When laying out the mine main power cables, junction boxes can be included in advance if the potential need for future charging stations is recognized. Junction boxes add some upfront costs, but will make it much easier to add charging stations in the future.

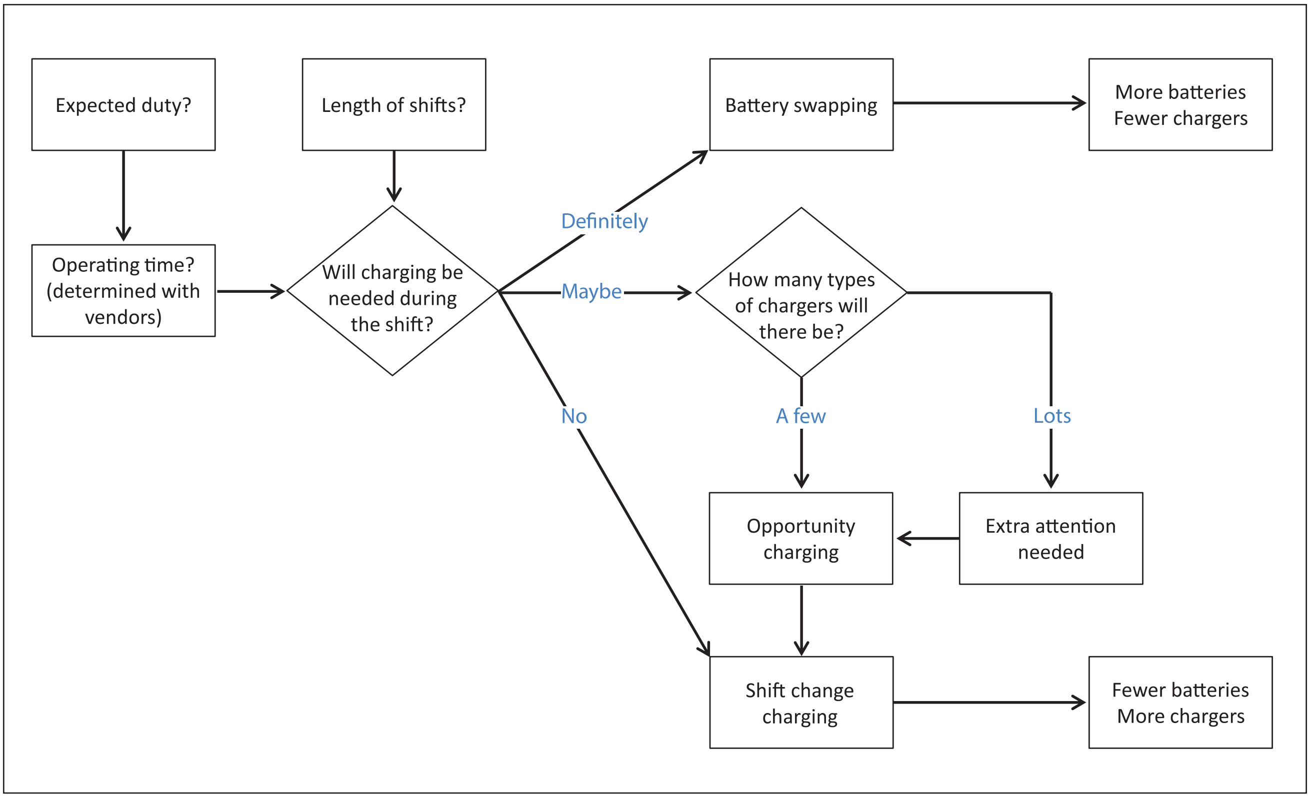


Figure 5. Charging System Design

6.5.2.1 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 described in Section 9.4 must be tailored to a given mine based upon many factors, including the following:

- The energy consumption model is an important first step: it will determine the operational plan and charging philosophy
- 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 to take advantage of BEV regenerative braking (Sections 6.2.2, 7.3, and 11.3.3).

Considerations for charging philosophy include the following:

1. Standardize the entire mine with one type of charger—to the extent possible.
    - If only small BEVs will be deployed and / or if charge time is not a significant concern, on-board charging may be the easiest option.
    - If one OEM will supply all (or most) of the BEVs, a proprietary off-board charger developed by that OEM may be appropriate.
    - If multiple OEMs will be supplying BEVs, a standard charging protocol such as combined charging system (CCS) Type 2 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 9.4.4) 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 6.3.1).
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.

  - For large BEVs (LHD machines and haulage trucks), install high-capacity chargers. These should be as powerful as possible (e.g., 150 kW or higher).
  - For small BEVs (man carriers, utility vehicles), chargers in the 20–50 kW range are sufficient.
  - If a large BEV is connected to a low-power charger, the charge proceeds but takes longer.
  - 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., 200–1,000 VDC).

The following points regarding battery running time should also be considered:

1. If the battery running time is longer than the shift length at the design duty, then shift-change charging is simple to implement.
2. 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.
3. 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.

6.5.3 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 needed to be filled with fuel and “away it goes” (Section 5.1).

6.5.4 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 kWh battery
Opportunity: 30 min. lunch break = 25 kWh energy (approx. 25% charge)
Typical shift-change: 2 h between shifts = 100 kWh energy (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 kWh battery
Opportunity: 30 min. lunch break = 50 kWh energy (approx. 50% charge)
Typical shift-change: 2 h between shifts = 200 kWh energy (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.

6.5.5 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.

6.5.5.1 Physical environment The physical environment considerations described below are illustrated in Figure 6.

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 6.6.4 for ventilation design to remove excessive heat)
- Vibration
- Percussion blast
- Falling objects
- 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

For further details on the physical environment requirements for charging refer to Section 9.

6.5.5.2 Spacing and parking Equipment spacing should follow OEM recommendations and local regulations. Charging cable manoeuverability 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., RS-232, Ethernet). Larger cables or different protocols could remove these restrictions, but at a cost that could outweigh the benefits.

6.5.5.3 Battery swap-out station design Similar to a typical diesel refuelling 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 (compatible with all BEV types that will use this system) to remove and install batteries on equipment and move batteries within the station
- 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

6.5.5.4 Remote battery swapping Instead of swapping batteries at a charging station, it may be advantageous to swap batteries where the BEVs are working. This would require a second means of battery transportation from the charging / storage area to the unit in need of a replacement and the tooling required to perform the battery swap at the BEV. This solution may add complexity and cost for procuring, maintaining, and operating the additional equipment, but it may be advantageous if the distance from the work

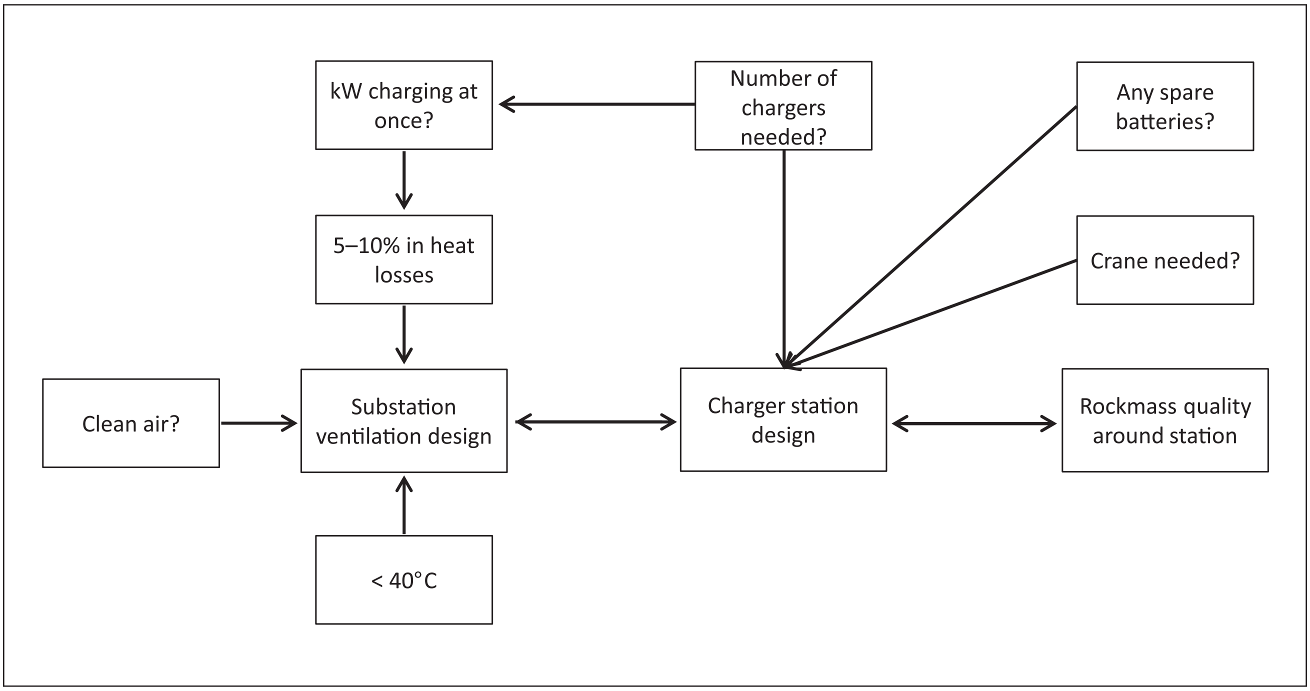


Figure 6. Charging Station Design Considerations

area or work cycle to the charge location is significant and / or the BEV has a slow tramming speed, ultimately resulting in increased charge related downtime.

6.5.5.5 Mine power distribution considerations Because most chargers operate with an incoming voltage of 400–1,000 V in 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 9.3). 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 high.

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 6.5.2) to prevent over-sizing transformers.

6.5.5.6 Fast charging considerations Due to the large size of mining equipment, as well as the duty cycle required by operations, most equipment would likely require a fast charger. As batteries approach their theoretical limits and fast charging chemistry becomes readily available, the high kilowatt demand for short time periods becomes considerable. Since a charger load is a 100% duty cycle, special attention must be paid to the timing at which the fast charging of different BEVs occurs and the location of the charging station. A charging schedule or automated method would prevent overloading the mine electrical system. Close attention must also be paid to the amount of heat generated during this process, either inside the machine or at the charging site.

6.6 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 achieving a good engineering design. The design criteria for an electric mine will be the same 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 DPM 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 air distribution system with all required infrastructure and controls (Tables 1 and 2).

6.6.1 Determining Air Volume

The process for determining air volume for battery-powered mobile equipment is based on heat, dust, and air velocity (Figure 7), whereas for diesel-powered equipment,

Table 1. 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 2. Ventilation design data considerations, sources and applications for electric equipment

Need	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 refrigeration plant	An economic analysis to determine if a refrigeration plant 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 recirculated?	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

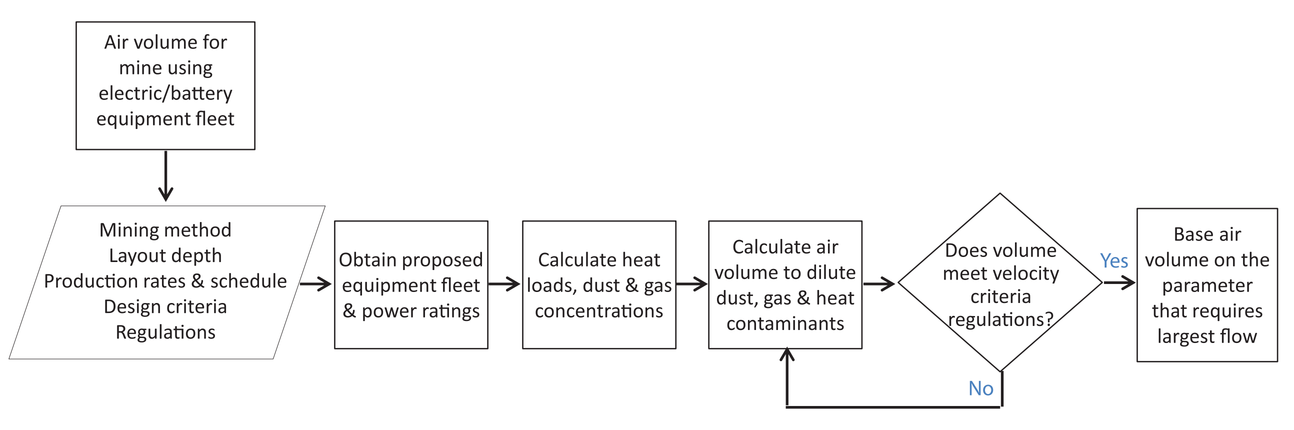


Figure 7. Air Volume Sizing Process for Battery-Powered Mobile Equipment

it is based on DPM, heat, and gas dilution (often dictated by government regulations). The sections below describe parameters specific to an electric mine, with some reference to diesel-powered equipment.

6.6.2 Regulations

Federal and local (applicable to the mine site jurisdiction) air quality regulations and standards will influence air volume requirements. 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.

6.6.3 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.

6.6.4 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 and BEVs), auto compression, and wall 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.

6.6.4.1 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 energy consumed minus the net work done (Section 11.3.6). Load / power profile curves obtained from the BEV vendor would facilitate determining the equipment kW ratings for the heat load determinations.

6.6.4.2 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. 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 temperatures in the charging area remain below the manufacturer's specified limits, to prevent electronic failures (Section 9.3).

6.6.5 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 data from the mine site occupational exposure monitoring program. It should be noted that BEVs don't have exhaust pipes and therefore do not stir up as much dust as diesel equipment. 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.

6.6.6 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 8), 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.

6.6.6.1 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 6.6.6.2). Airway placement needs to consider conditions unique to an electric mine layout, such as number and size of substations and charging stations.

6.6.6.2 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. Study results will be

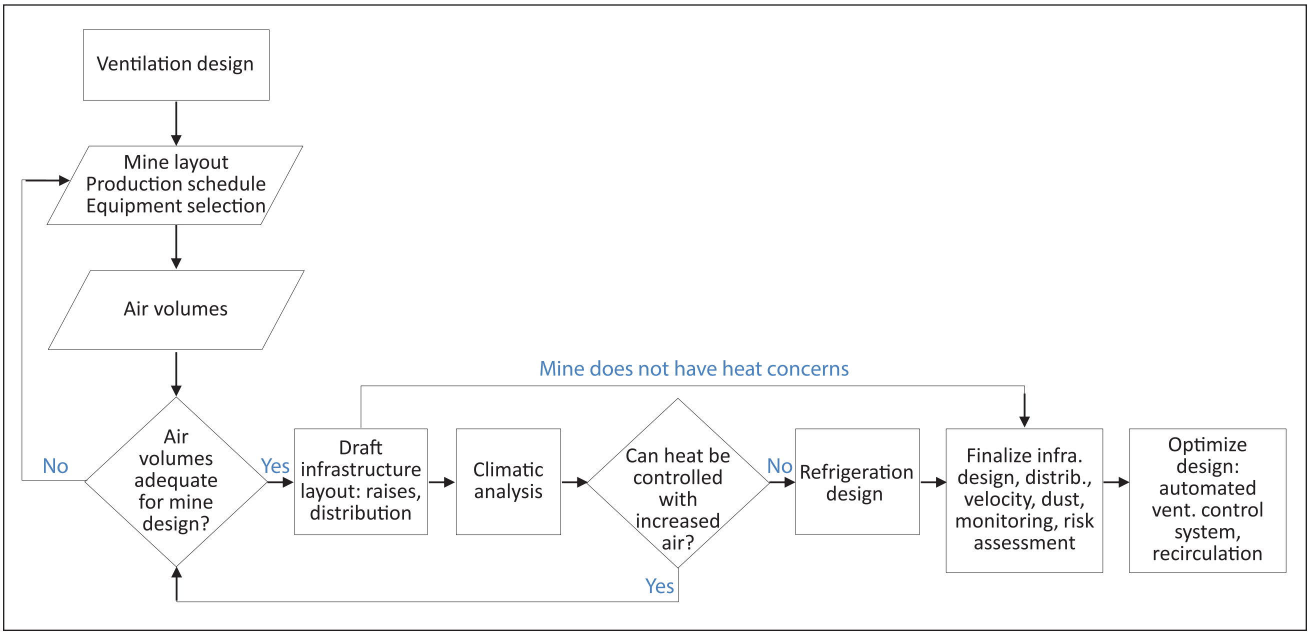


Figure 8. High-Level Ventilation Design Process

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 verified to remain within the design criteria limits.

6.6.6.3 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 reaching the workplace. Once a preliminary ventilation design is complete, a review of the clearing time should be conducted 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.

6.6.6.4 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.

6.6.6.5 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 was part of the design, fixed monitoring would be required to ensure regulatory compliance of air quality.

6.7 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 (DPM, dust, and moisture)
- Heat
- Fire
- Geotechnical aspects

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 and the ease or difficulty to reach personnel if they require rescue. The adoption of BEVs can reduce the potential for fire by minimizing or removing diesel fuel and hot engine sources of ignition from the underground environment. However, there are unique issues associated with fighting a fire on a BEV, which should be identified (i.e., special labelling) to protect mine rescue personnel from harm. Depending on battery chemistry, uncommon gases could be released into the ambient atmosphere during normal operation, charging, and fire. These gases must be considered in the mine design (Section 8.3).

7. BATTERY ELECTRIC VEHICLE DESIGN

7.1 Introduction

In addition to electric traction motor(s), BEVs comprise an operator interface, braking system, electrical system (including the battery and BMS), and in some cases, an on-board charging system (Section 9.4.1). Depending upon the design, a given BEV may use: a transmission; a clutch, gearbox, differential, and fixed gearing; and battery packs and motors (Figure 9). Overall, BEV design must integrate the strong relationship between the design of the electric motor and other BEV components.

7.2 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 3). 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 state of charge (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 3) 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

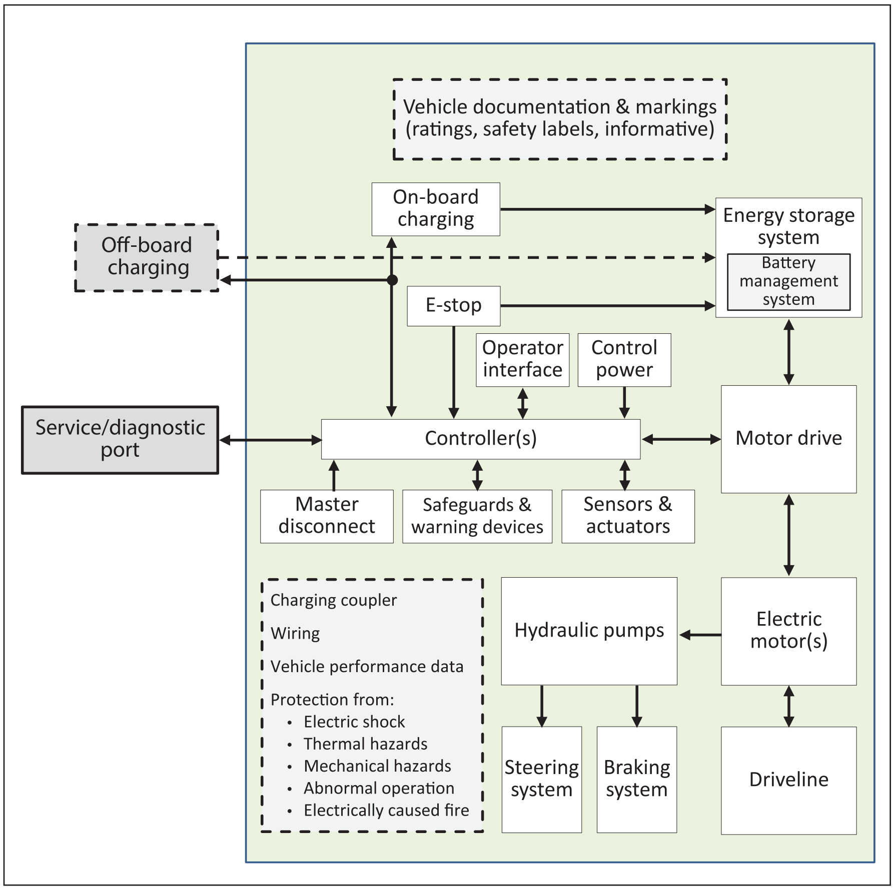


Figure 9. Representative BEV Block Diagram. Some functions are not indicated for simplicity.

Table 3. 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 12.

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 13766-1:2018	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, 2018a
ISO 13766-2:2018	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, 2018b
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, 2007a
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, 2015a
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, 2016b
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

Table 3. (continued).

Recommended Industry Standard	Topic	Jurisdiction	Citation
IEEE C95.4-2002	Recommendations to prevent inadvertent detonation of electric initiators by radio-frequency electric and magnetic fields generated from transmitting antennas (0.5 MHz to 300 GHz)	International	Institute of Electrical and Electronics Engineers Standards Association, 2002
M421-16	Minimum requirements for electrical work and electrical equipment operating / intended to operate at a mine	Canada	CSA Group, 2016b
SLP 20	Suggest guidelines for the safe use of commercial electric detonators near radio frequency energy sources	USA	Institute of Makers of Explosives, 2011
SLP 22	Recommendations to allow sufficient time in the event of a transportation incident involving explosive materials to evacuate bystanders to a safe distance	USA	Institute of Makers of Explosives, 2007
Directive 2014/35/EU	Laws relating to making available on the market electrical equipment designed for use within certain voltage limits	European Union	Official Journal of the European Union, 2014
ISO 15817:2012	Safety requirements for remote operator control systems used on earth-moving machinery as defined in ISO 6165:2012	International	International Organization for Standardization, 2012c
ISO 17757:2017	Safety requirements for autonomous and semi-autonomous machines and systems used in earth-moving and mining operations	International	International Organization for Standardization, 2017c
AS/NZS 4240.1:2009	Requirements for the design, construction, testing, installation, commissioning, and modification of remote control systems for mining equipment and machinery	Australia and New Zealand	Standards Australia, 2009

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 7.3). The regenerative braking state (on or off) should always be clearly displayed on the operator interface.

7.3 Braking System

The vehicle must have a service brake system, a secondary braking system, and a park brake system as defined in ISO 3450:2011 and CAN/CSA-M424.3-M90 (Table 3).

Definitions:

1. **Service brake system** – As defined in EN ISO 3450 and CAN/CSA-M424.3-M90; can include electric or electromechanical braking through the application of dynamic braking.
2. **Secondary brake system** – As defined in EN ISO 3450 and CAN/CSA-M424.3-M90.
3. **Park brake system** – As defined in EN ISO 3450 and CAN/CSA-M424.3-M90; can include electric or electromechanical braking through the application of dynamic braking.
4. **Dynamic braking** – The use of an electric traction motor as a generator when slowing a vehicle such as an electric or diesel-electric locomotive. It can be rheostatic, regenerative, or a combination of the two.
5. **Rheostatic braking** – The generated electrical power is dissipated as heat in brake grid resistors.
6. **Regenerative braking** – The power is returned to the supply line and ultimately back to the energy storage system.
7. **Braking resistor** – A resistive element used to dissipate kinetic energy that was transformed into electrical energy due to "dynamic" or "regenerative" braking.
8. **Supply line** – The cable supplying power from the battery to the motor inverter.

The following should be noted regarding dynamic braking:

1. Rheostatic braking must have the capacity to dissipate the braking power. Given the current state of the technology, this is typically accomplished by the use of grid brake resistors. In larger BEVs, it may not feasible or practical to install this magnitude of brake resistors.
2. Regenerative braking requires reserve battery capacity in which energy can be returned to the battery by way of the supply line. This requires that the battery SOC can fully accommodate absorbing this energy at all times or the system combines battery capacity and grid brake resistor capacity.
3. An electric traction motor requires an electric supply to hold a vehicle stationary against an external force. If this electric supply fails, the motor will no longer be able to hold the machine stationary. Thus, if the battery of a BEV is disconnected, the motor will not be able to hold the BEV stationary on a

ramp. The secondary braking system must take over in this scenario.

To be consistent with conventional drivetrains, when using an electric motor and electrical energy storage system as the main traction drive, any loss of electrical coupling between the rotor and stator of the electric traction drive should automatically apply the secondary braking system in compliance with ISO 3450:2011 and CAN/CSA-M424.3-M90 (Table 3). The secondary braking system should be applied automatically following the activation of a warning after the system senses an unsafe condition from the battery monitoring system, BMS, or vehicle control system in conjunction with 4.3.2.2 of CAN/CSA-M424.3-M90. The braking system circuit shall be designed in accordance to ISO 13849-1 and tested in accordance to ISO 13849-2, ISO 3450:2011 and CAN/CSA-M424.3-M90 (Table 3).

7.4 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 3). Applicable local 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 conform to ISO 13766-1:2018 and ISO 13766-2:2018 (Table 3), which outline requirements and limit values for electromagnetic (EM) emission and immunity to external EM 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 OEM, and the system integrator or OEM. The BMS communicates with charging infrastructure and emergency shutdown subsystems (Sections 8.1–8.3).

7.4.1 Electrical Interference with Blasting Caps

The risk of interference with blasting caps is a particular concern. Recommendations regarding prevention of this electrical interference can be found in IEEE C95.4-2002 (Table 3). Standard M421-16 (Table 3) clause 4.7.4.1 states: "Blasting-circuit conductors shall be kept at least 150 mm away from power or lighting cables and, where possible, shall be run on the side of the working opposite power and lighting circuits." Standard M421-16 clause 4.7.4.3 states: "Blasting-circuit conductors shall not come into contact with pipes, rails, or other electrically conductive materials that might be accidentally energized or vulnerable to static charges."

7.4.2 Extraneous Electricity

Guidelines should be consulted to ensure that an electric detonator is not used if extraneous electricity at the blasting area exceeds a given limit (e.g., 50 mA in the United States; Occupational Health and Safety Administration, 1996).

7.4.3 Minimum Distances from Radio Frequency Transmitters

During electric blasting, an employer and a blaster must ensure minimum distances from radio frequency transmitters are maintained as detailed in the Standard SLP 20 (Table 3). Recommended minimum distances are "100 m from a citizens' band radio, cellular telephone, satellite telephone or other mobile or portable radio frequency transmitter; and… 1000 m from a TV transmitter or an AM, FM or other radio frequency transmitter" (Institute of Makers of Explosives, 2011).

7.4.4 Transportation of Electric Detonators

If electric detonators are in their original containers, current evidence indicates that radio energy is not a hazard in their transportation because the wires are coiled or folded in a manner that provides highly effective protection against current induction. Furthermore, most truck bodies and freight cars are made of metal; this virtually eliminates the penetration of radio frequency energy. Electric detonators not in their original containers must be transported in a SLP 22 compliant box (Table 3). The barrier laminate design of such a box includes a layer of steel or sheet metal, shielding of the detonators from radio frequency energy. If vehicles equipped with radio transmitters are used to transport electric detonators, it is recommended that the transmitter is turned off when the detonators are placed in or taken out of the box. To protect against shock and friction, the box should be lined with soft material such as wood or sponge rubber.

7.5 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 3) should be met.

7.6 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. Local mining regulations or site level risk assessments may also require an automatically activated system. Fire-fighting information to train operators, mechanical and 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.

7.7 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 ruggedly constructed and designed to facilitate inspection and maintenance by a skilled person as defined in IEC 60050-826:2004 (Table 3):

- 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 components
- Access openings in enclosures located only where necessary for maintenance or inspection
- High- and low-voltage components separated
- Enclosures where access is for maintenance personnel only; 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 3) or be touch-safe

7.8 Emergency Stop

If the hazards and risks inherent to a BEV energy storage system cannot be eliminated or sufficiently reduced by safe design, an emergency stop function should be included in the BEV design that complies with ISO 13850:2015 (Table 3), which deals with safety aspect(s) or one or more types of safeguard that can be used across a wide range of machinery.

7.9 Master Disconnect

A BEV should incorporate one or more manual master disconnect devices (possible configuration illustrated in Figure 10), which 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.

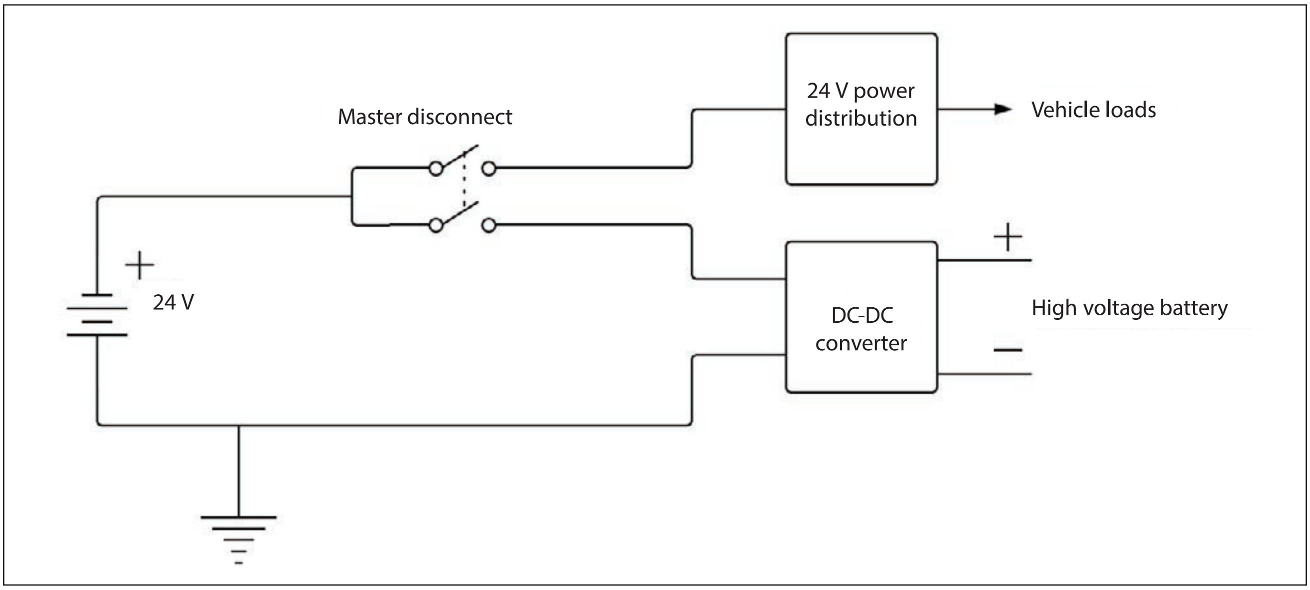
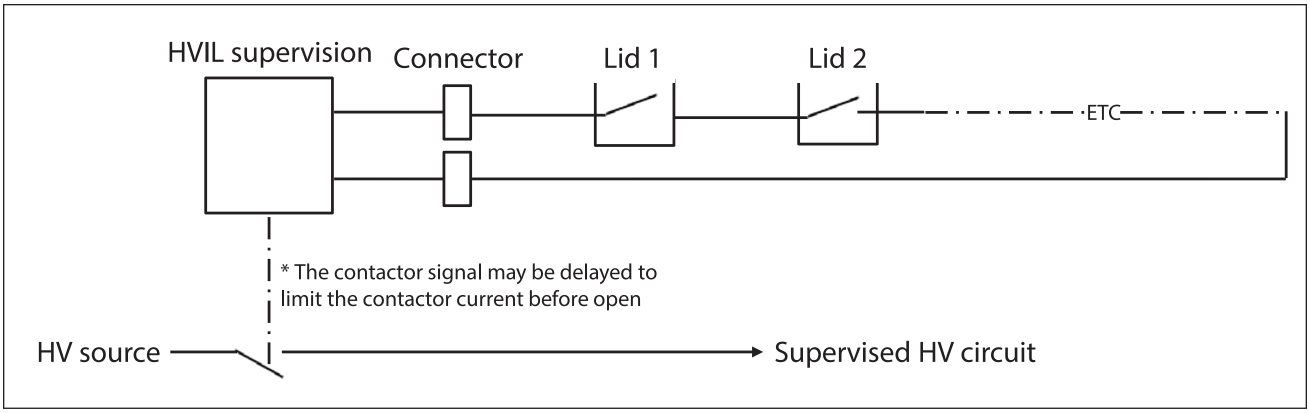


Figure 10. Example of a Master Disconnect Device

7.10 Hazardous Voltage Interlock

A hazardous voltage interlock loop (HVIL) should be used to prevent direct exposure of hazardous voltage on BEVs (Figures 11 and 12). It should be used for lids and connectors that don't fulfill IP class IP2X code (International Electrotechnical Commission, 2013a) when open. The HVIL can be one loop covering all components or several loops covering different parts of the machine. It should be monitored to detect faults in the circuit. Opening the HVIL loop will trigger a power shutoff for the battery power outlet. The shutdown can be delayed to make it possible to reduce current through power contactor(s). The function may be



* The contactor signal may be delayed to limit the contactor current before open

Figure 11. Conceptual Diagram of a Hazardous Voltage Interlock Loop (HVIL)

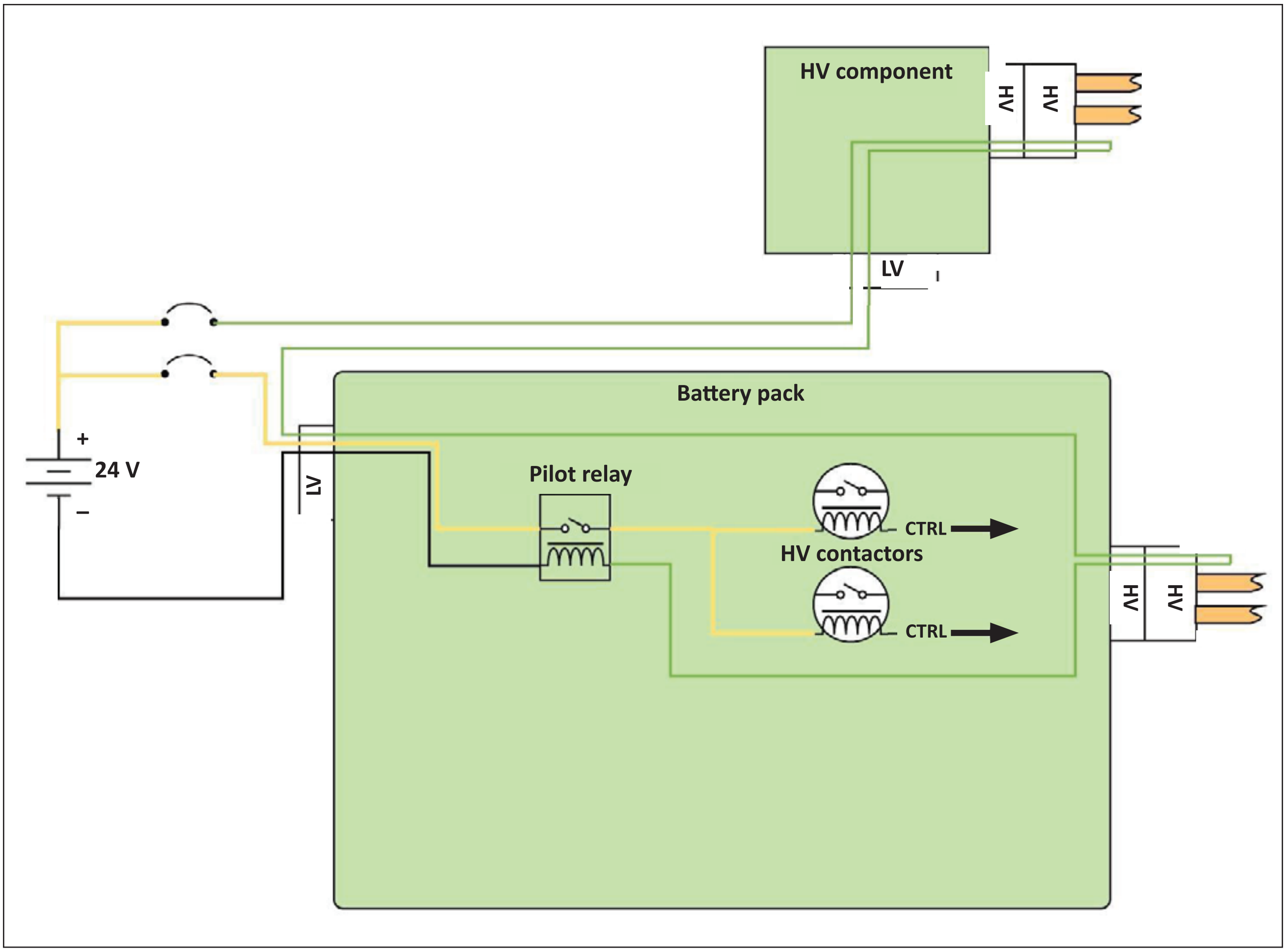


Figure 12. Example of a Hazardous Voltage Interlock Loop (HVIL)

supplemented with discharge function for hazardous voltage to decrease discharge time. A separate circuit can also be used to monitor harnesses with hazardous voltage that are protected against direct contact. A fault in such circuit may only result in a warning.

7.11 Insulation / Ground Fault Monitoring

High-voltage energy is always present in a BEV 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 3). 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 BEV.

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 BEV should be inspected and repaired by trained service personnel as soon as possible.

7.12 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 3) cover overall risk assessments.

7.12.1 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.

The 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).

7.12.2 BEV Firmware / Software Risk Assessment

Standard industry practice is to complete a risk assessment when new equipment or technologies are introduced into the mining environment. It is highly recommended that a risk assessment is completed whenever BEVs, charging systems, and other BEV support equipment are planned for a mine. BEVs often use firmware / software systems to monitor, protect, and communicate the state of the battery system within the vehicle. In these situations, a risk assessment should include identification and analysis of any firmware / software controls that directly impact critical functions or identified risks.

Differences in design and applications of BEVs mean a detailed recommendation is not possible. Rather, it is recommended that during the risk assessment process, mine operations work closely with the BEV OEMs to identify firmware / software-based functions that should be included in the risk analysis. A firmware / software risk review should consider (but not be limited to) braking systems, steering systems, personal protection systems, and fire and other hazard protection systems. Software risk assessments should be performed for all software updates, as well as new equipment. If it is determined that critical functions are controlled by firmware / software systems, then a deeper analysis of the identified risks is warranted.

7.12.3 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 3).

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.

7.12.4 BEV Maintenance

As noted in Section 7.10, 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, 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. Other key considerations for BEV maintenance include:

- OEM(s) should provide procedures for towing to prevent creation of dangerous voltages.
- Service areas on a BEV should be designed to prevent unintentional contact with hazardous moving parts and voltages when adjusting or resetting controls or performing work similar to that 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 accessed without tools 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 labelled with a warning symbol and a notice of where to obtain appropriate maintenance procedures and should require tools for access.
- Battery electric systems of 75 VDC or higher main system voltage should be identified according to Directive 2014/35/EU (Table 3).

7.12.5 Considerations for Remote Control

Several factors must be considered when designing a system to be controlled remotely. This section highlights important factors that are unique to—or may be of special significance to—BEV design. The list is not comprehensive: all the factors typically used in a diesel-powered application must also be considered. The relevant standards and regulations are ISO 15817:2012, ISO 17757:2017, and AS/NZS 4240.1:2009 (Table 3).

1. Communicate SOC and warnings to remote operator
2. Does charging infrastructure need to be automated or remotely controlled?

7.12.6 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 3). See Section 8.2.9 for additional guidance on BEV component handling at end-of-life.

8. ENERGY STORAGE SYSTEMS

8.1 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 5.1) and is thus 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 4). Lead-acid batteries have long

Table 4. Rechargeable battery types (https://en.wikipedia.org/wiki/Lithium-ion_battery; 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	0.36–0.900	2.3–4.2

been—and continue to be—used in conjunction with fossil fuels to power cars, boats, and other vehicles.

Given the relatively high energy density of LIBs (Table 4), they are currently the most common choice for 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 (Figure 13a). The electrolyte is a mixture of lithium salt and organic solvents in liquid or gel form. Another commercially used battery type is a molten salt battery, where the electrolyte is sodium chloride that is kept at a temperature high enough for it to be liquid (Figure 13b). Additionally, the possibility of using ultracapacitors (very high capacity electrical capacitors) has been proposed, either on their own or in combination with batteries (Figure 13c).

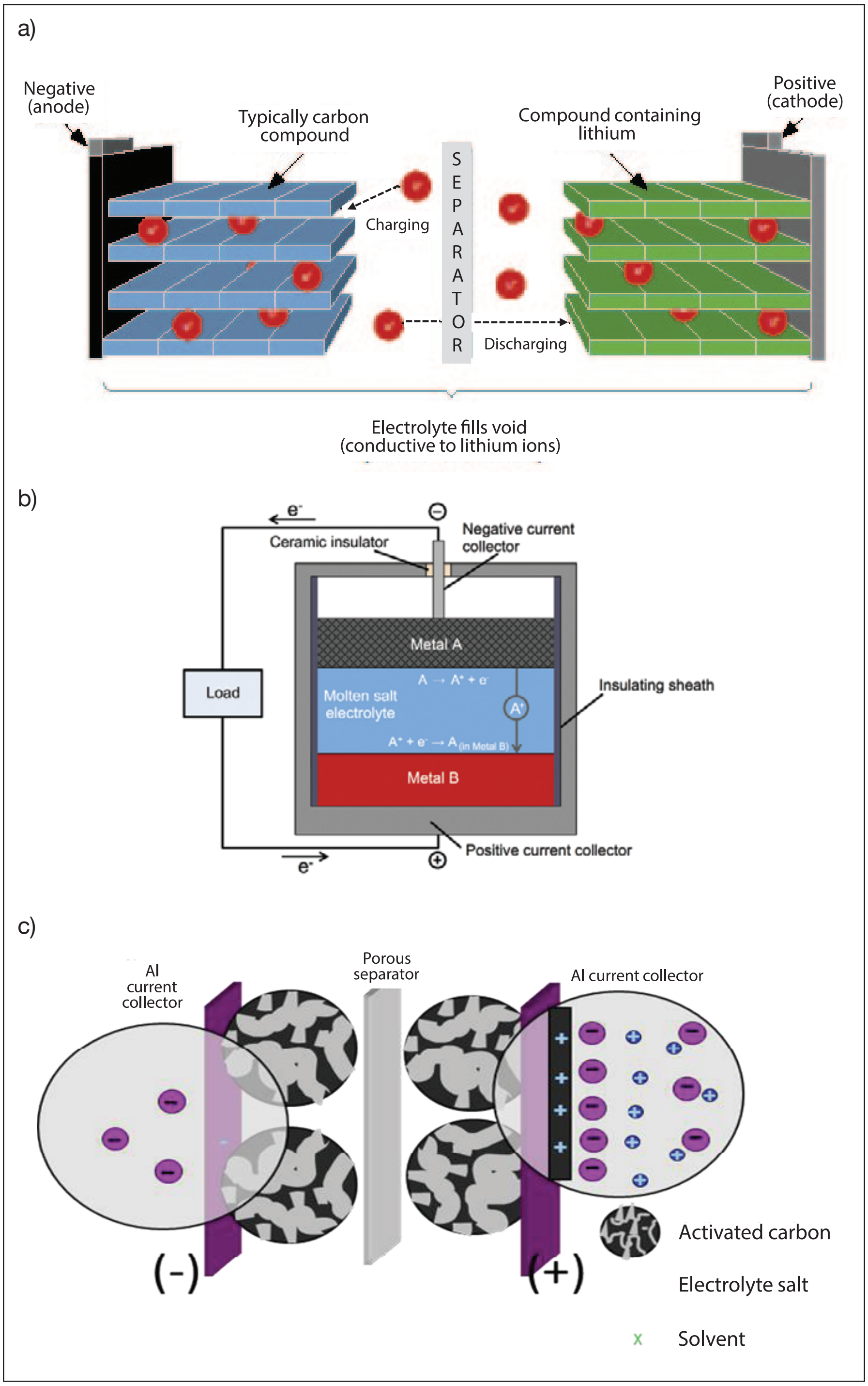


Figure 13. Conceptual Sketches of a) Lithium-Ion Batteries, b) Molten Salt Batteries, and c) Ultracapacitors

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 8.1, 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.

The BMS contains a significant amount of data related to the operation, performance, and health of the battery. While some of the data are proprietary to the OEM, the rest can be very valuable to the equipment operator to help them understand how the battery is performing. A guide to which data are proprietary vs. available to the operator can be found in the Global Mining Guidelines Group (2016).

8.2 Functional Requirements

8.2.1 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.

8.2.2 Thermal Management and Testing

Within a battery, heat is generated by the current flow (the Joule effect); temperature management is within 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 is the result of an external heat source or the voltage and / or current being out of the operating range. High internal temperatures can cause separator failure, leading to internal short-circuiting. For some chemistries, internal shorting can lead to thermal runaway, 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 8.3), elevated temperatures accelerate the degradation of capacity and power in LIBs, and can cause charge imbalance among battery cells.

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

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 12.

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
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, 2018
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

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.

8.2.3 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 within 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).

8.2.4 Fire Prevention and Suppression

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

8.2.5 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 by disconnecting the main battery contactors if operating parameters exceed allowable operating parameters. The automatic shutdown of the system should be designed and tested to comply with IEC 61508:2010 and IEC 62061:2005 (Table 5).

8.2.6 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

8.2.7 Extreme Temperature Considerations

Operating a BEV in temperatures outside the normal operating zone of the battery chemistry will almost always be a compromise between 1) reduced range and 2) requiring a larger capacity energy storage system to offset the parasitic draw from the additional systems required to raise or lower temperatures to bring the battery into the desired operational span.

Modern diesel engines are more mechanically efficient than ever, yet they only convert approximately 44% of the fuel's energy into mechanical work: 56% is converted to heat. This waste heat helps offset the adverse effects of the cold and improves operator comfort. By contrast, electric motors typically have mechanical efficiencies exceeding 90%. Thus, at most 10% of the energy is converted into heat. Many battery chemistries and electrical components on BEVs are temperature sensitive and can be irreparably damaged if subjected to temperature extremes. A suitably designed BEV considers the effects of low ambient temperature, not only on the energy storage and tractive systems, but on the passenger compartment heating and window defrosting systems.

Conversely, in extreme heat conditions, cooling the battery can be a challenge. The upper limit of several popular chemistries can be near ambient air temperature, which may not leave a large enough delta for a traditional radiator system to be effective. In these instances, a more advanced cooling strategy (e.g., heat pump system) may be needed.

8.2.8 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 3). 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

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. These documents outline safe handling and storage practices for battery systems that have been physically damaged or subjected to high or low 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.

8.2.9 End-of-Life

Energy storage systems in BEVs have a limited life and will eventually wear out. End-of-life for the battery system or individual replaceable components of the system should be fully defined by the OEM. 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 compliance with specifications. Regardless of the approach taken, before the battery system is transported, it will need to be packaged and labelled according to requirements, which vary by geographic location. The battery system OEM should be contacted for detailed instructions. While not universal, many transportation regulations, including the United States Department of Transportation, Canada Transportation of Dangerous Goods, International Maritime Dangerous Goods Code, and Australian Code for Transport of Dangerous Goods, as well as the International Air Transport Association Dangerous Goods Regulations require use of packaging designed and tested to the United Nations Recommendations on the Transport of Dangerous Goods, Model Regulations (Section 38.3 for lithium metal batteries and LIBs). Whereas disposal of used battery systems may not be a primary consideration in planning a battery electric mine, a plan for disposal should be considered early in the planning process due to the complexity of transportation regulations and the potential costs of disposal.

Recycling of lithium ion cells is an alternative to disposal as waste; however, recycling LIBs at present is likely to provide more ecological than economical benefits. The wide range of materials present within a lithium ion cell, materials used in the battery system packaging, and the potential for the cells to hold significant amounts of stranded energy together make recycling a complicated process. It is anticipated that as LIB systems become more prevalent (especially in the automotive industry), new battery construction techniques and recycling processes will improve the economics of recycling.

A third option to consider at end-of-life—commonly referred to as “second life”—is becoming available. Battery systems at end-of-life often have 70–80% of their storage capacity. Used, undamaged LIB systems are finding a second life in applications such as power grid stabilization systems and residential photovoltaic storage systems and could last many years at this reduced capacity. Similar to recycling of LIBs, the market for these second life applications has not yet fully matured. LIB systems have become more prevalant in propulsion systems; therefore, a significant increase in the quantity of battery sytems available for second life applications will follow and will likely drive growth in second life applications.

The significant amounts of energy in a worn-out battery system and the presence of materials that may require special handling, recycling, or disposal methods based on local laws are key safety considerations. Mine operators should never attempt to disassemble, dispose of, rebuild, or repurpose a battery system without contacting the OEM for instructions. Disposal / recycling and transportation methods at the battery system end-of-life should always be made in consultation with the battery system OEM and local laws. Components containing hazardous materials should be properly labelled 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 labelling should also include OEM contact information.

8.3 Safety Requirements

8.3.1 Hazard Conditions: Causes 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 (Table 6):

Table 6. Hazard conditions for lithium ion batteries (Mikolajczak, Kahn, White, & Long, 2011).

Hazard	Cause	Comments
Thermal runaway	Over-charge, over-voltage	Can cause lithium plating, where lithium ions deposit dendritic metallic lithium on the anode, leading to a potential short-circuit. Can also lead to increased temperatures.
	Over-temperature (70°C)	Can cause degradation of the solid electrolyte interface (SEI) layer on the anode, which if breached, allows the electrolyte to react with the anode in a high-temperature exothermic reaction. Does not apply to lithium titanate anodes, which do not depend on the SEI layer.
	Over-discharge, under-voltage	Can cause anode copper to dissolve in the electrolyte, which may form dendritic metallic copper when the cell voltage is increased, leading to potential short-circuit.
	Over-current, rapid charge and discharge	High currents can increase the temperature of the cells. See over-temperature.
	Internal short-circuit due to cell defect	Possible defects include: component deformation, blocked separator pores, uneven anode coating, uneven contact between separator and anode, delamination of current collector, contamination, and dry electrolyte.
	Internal short-circuit due to lithium plating, precipitated anode copper	Caused by over-charge or over-discharge.
	Mechanical damage, abuse	Puncturing a cell would damage the SEI layer on the anode and cause a high-temperature exothermic reaction between the anode and electrolyte.
	External heat source, fire	See over-temperature.
Venting	Thermal runaway	Breakdown of organic solvents in the electrolyte into highly toxic and flammable gases.
Combustion of battery cells	Thermal runaway	May occur when the flammable gases are released and mix with oxygen if the temperature is high enough or if there is an external sources of heat or spark.
Rapid disassembly of battery module	Thermal runaway, poor venting	Battery module may explode if the gases produced during thermal runaway are not allowed to vent to the atmosphere.
Venting with flame, ignition of vented gas	Thermal runaway, high temperature, external spark	External sources of heat or spark near battery vents.

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 likelihood of the above risks depends on the battery chemistry and how the OEM battery design mitigates and addresses the risks.

The cumulative effects of electrical and chemical hazard conditions can lead to thermal runaway (Section 8.2.2). 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.

An internal short-circuit caused by contamination during manufacture with microscopic metal particles can go undetected and initiate thermal runaway. During a thermal runaway, the high heat of the failing cell can propagate to the next cell, causing it to become thermally unstable as well. In some cases, a chain reaction occurs, in which each cell disintegrates at its own timetable. A battery pack can be destroyed within a few seconds or linger for several hours as cells are consumed one-by-one. To increase safety, some packs may be fitted with dividers to prevent cell failure from spreading to neighboring cells.

Another safety issue is cold temperature charging. Some LIBs cannot be charged below 0°C. Although the packs appear to be charging normally, plating of metallic lithium occurs on the anode during a sub-freezing charge. The plating is permanent and cannot be removed. If done repeatedly, cold temperature charging can compromise the safety of the pack, making the battery more vulnerable to failure if subjected to impact, crush, or high-rate charging.

8.3.2 Hazard Condition Monitoring, Prevention, and Mitigation

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 8.3.1 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 to 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 7–10 are prevented by appropriate battery mechanical protection, usage, and handling.

Hazard conditions during charge, discharge, and storage can be prevented by avoiding exposing batteries to heat and fire (e.g., welding on or near batteries) and electrical abuse (Recharge, 2013). In the event of a hazard condition, mitigation measures reduce sensitivity, reduce the reaction (e.g., manage fire and 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.

It should be noted that some failure modes, such as dendrite formation and subsequent internal short-circuit, cannot be completely detected or prevented, and the statistical likelihood is that they will eventually occur. OEMs should provide a response plan for these events and their effects.

8.3.3 Transportation

Packaging, labelling, and notification precautions must be taken when transporting batteries for use or at end-of-life (Section 8.2.9). Applicable regulations depend on the geographical region(s) among which batteries are being transported and the 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.

Damaged 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 labelling 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.

9. CHARGING SYSTEMS

9.1 Introduction

Since chargers are an integral part of the BEV system, the charging philosophy (Section 6.5.2) needs to be established and understood early in the charging system 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 can be 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 7). Thus, a major hurdle to overcome when introducing BEVs into a mine is a strategy for charging all BEVs. As noted in Sec-

Table 7. Example of fleet vehicles

Equipment	Fleet	Power (kW)	Loaded weight (kg)	Battery (kWh)	Range for 15% grade (km)
Haulage / water trucks	8	300	60,000	400	8
LHD machines	14	250	60,000	200	4
Graders	1	100	20,000	200	12
Drill and bolters	12	125	25,000	100	4
Emulsion loaders	4	150	15,000	100	8
Large utility vehicles	15	150	15,000	100	8
Small utility vehicles	30	100	5,000	50	12

tion 6.5.2.1, a simple and standardized charging interface is key to making BEV charging simple, convenient, and safe.

Although OEMs have their own packaging specifications and requirements, mine-specific packaging requirements 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
- 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 8). Further, the final installation of the chargers should respect the local practices, and undergo any approvals or inspections that may be necessary.

9.2 Safety Considerations

While working with the charging system and in or near the BEV, workers are exposed to EM radiation. The International Commission on Non-Ionizing Radiation Protection 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 8).

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 (Table 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. This section details safety features that should be universal among charging systems and safety features for specific charger types.

9.2.1 Installation

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

Table 8. 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 12.

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 62196-1:2014	Applies to plugs, socket-outlets, vehicle connectors, vehicle inlets and cable assemblies for BEVs	International	International Electrotechnical Commission, 2014a
IEC 62196-2:2016	Applies to plugs, socket-outlets, vehicle connectors and vehicle inlets with pins and contact-tubes of standardized configuration	International	International Electrotechnical Commission, 2016a
IEC 62196-3:2014	Applies to vehicle couplers with pins and contact-tubes of standardized configuration	International	International Electrotechnical Commission, 2014b
SAE J1772_201710	General physical, electrical, functional, and performance requirements to facilitate conductive charging of BEVs and plug-in hybrid electric vehicles	North America	SAE International, 2017
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 supply equipment	Europe	Deutsches Institut für Normung e. V., 2014
SAE J3105 [WIP]	Electric vehicle power transfer system using a mechanized coupler	International	SAE International, 2012
IEC 60664-1:2007	Insulation coordination for equipment within low-voltage systems	International	International Electrotechnical Commission, 2007b
IEC 60364-5-52:2009	Selection and erection of wiring systems	International	International Electrotechnical Commission, 2009

- Ventilation / cooling system
- Clearly identified parking spaces for BEV
- Drainage system and sump to limit mud and water in the charging area, especially after washing down
- Overhead support of charging cable (if required)
- 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 or integrated earth leakage / ground fault (GF) protection device (GF circuit interrupter)
- Ground path
  - Charger is tied to mine ground grid
  - When plugged in, BEV has a path to ground via charge cable
- Protection against ingress of dirt and water into charger connectors

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 BMS of the BEV is in "master" mode. Therefore a variety of chemistries can be charged, as long as appropriate standards are implemented.

The installation of the charger should comply with local codes (Table 8). Further considerations for the charging station include:

- Adequate space for personnel to safely operate and maintain
- Level floors that can be easily cleaned (concrete if possible)
- Adequate visibility and lighting of battery charger controls
- Compatibility with planned type of charging system (i.e., fixed, cable connected / temporary, or fixed for operation but easily transported to other areas)

There may be value in installing the power electronics in a dedicated charger electrical room. A decentralized human-machine interface would then be installed at the charging area. Be aware that voltage drop may be an issue. An alternative is to move the charger around as needed—subject to the mining strategy in use.

Given how often BEV batteries require recharging, exposure to potential hazards frequently occurs when workers connect, operate, and disconnect the charging system. This section includes design and procedural guidelines to minimize these risks. The overall goal is to ensure a safe charge via sufficient handshaking, communication, self-tests, and "ramp up" of the charging process.

9.2.2 Operation and Maintenance

The charger connector cannot be removed until the charger is turned off and similarly, charging cannot be initiated if the connector is unlocked. If the lock is opened during charging, power flow must be stopped immediately to prevent arcing and lethal shocks.

If the BMS detects a fault / problem during the charge process (e.g., battery gets too hot or the cooling system is not working), the vehicle BMS must report to the charger and stop the charge. In addition to the BMS, the charger must have features to protect itself if the connection to battery is faulted. In case of charger input power failure, the charger will prevent back-feed of power by physically isolating the BEV from the charger at the DC output on the charger.

Maintenance should be performed according to OEM recommendations.

9.3 Incoming Power System

The power system in an underground mine often extends to great depths and distances, providing power for all underground loads (e.g., ventilation fans, dewatering pumps, and mobile equipment). These loads can be large and start and stop frequently during a day. As noted in Section 6.5.5.5, 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 6.5.5 for further details on power system design.

The power requirements for a specific charger will be specified by the OEM. Additional considerations are as follows:

- Distribution equipment located within a distance that ensures system strength
- Generally, mine power distribution systems with chargers should comply with IEEE-519-2014 (see Table 8 above).
- Incoming short-circuit rating / withstand capability
- Input power requirements: voltage, current, frequency, phases, grounding, and isolation

- Voltage fluctuations and other typical mine power challenges in the mine grid

9.4 Types of Charging and Connection Interfaces

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

As described below, the charger system is not a consideration for on-board charging from an AC supply (Figure 14) 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. The cord set should be easily replaceable, in case it is damaged or needs to be longer (i.e., better to use a longer cord rather than adding an extension).

With an on-board charging from AC supply arrangement, the connection to the BEV is via an AC plug (Figure 14). Equipment for converting AC to 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.

9.4.1.1 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, one approach might be to adapt mobile equipment connectors for drills and bolters in diesel-based mines to charging BEVs. This seems to be straightforward: it requires very little fixed infrastructure, the BEV OEM would supply everything on the BEV (including an on-board charger), and it would simply be a case of connecting the charger to the AC supply to charge the equipment. 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 might appear to be the most convenient and simple option, OEMs for on-board charging BEV and drivetrain have identified several concerns (Section 9.4.1.4).

9.4.1.2 Charging interface During charging, a connector carrying AC is brought to the BEV. Because the power conversion equipment is on board the BEV, so too is most communication needed to regulate charge rates. 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 (Table 8) and vary depending on locale. For North America, BEVs have standardized on the IEC 62196 Type 1 (SAE J1772) connector (Table 8; Figure 15). The five pins have three

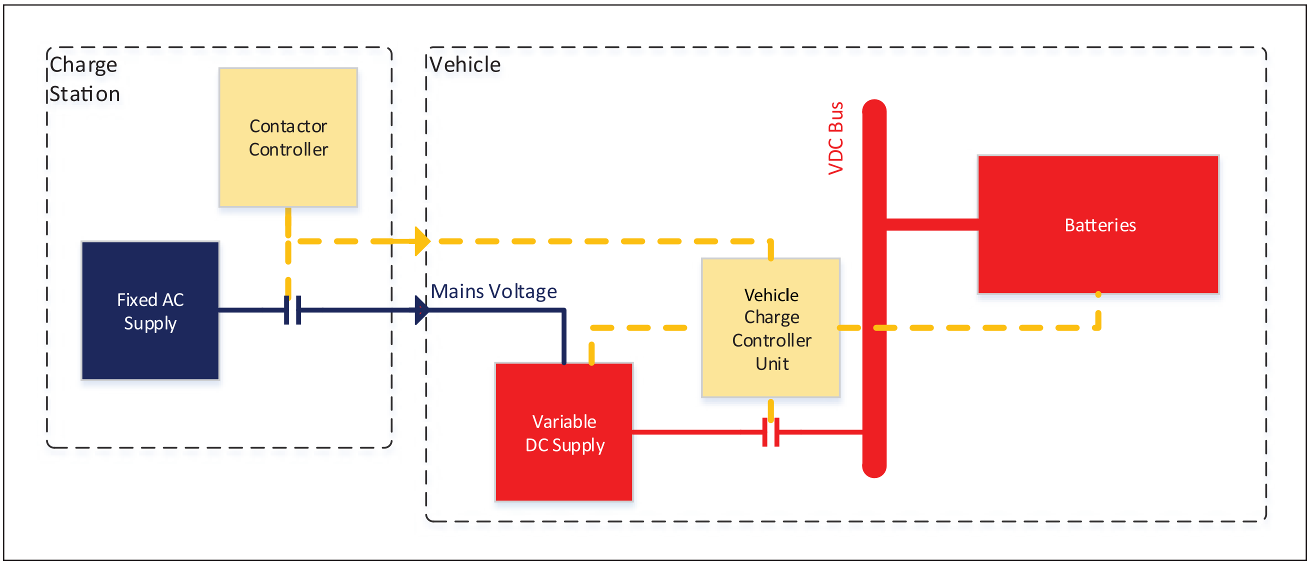


Figure 14. Typical On-Board Charging Arrangement

Figure 15. SAE J1772 Connector (SAE International, 2017)

sizes, from largest to smallest: AC line 1 and line 2; 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 is employed, supporting a higher voltage but lower current, delivering up to 22 kW.

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

Another option for on-board charging is to use conventional underground mining AC plugs.

9.4.1.3 Advantages of on-board charging

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.

9.4.1.4 Disadvantages of on-board charging

1. It is difficult for BEV OEMs to accommodate batteries and drivetrain equipment on large equipment such as LHD machines and haulage trucks. A large capacity, on-board charger—including power electronics (and sometimes a transformer)—adds to this challenge. Ergonomics and operator visibility may be compromised.
2. The added weight and volume of the on-board charger consumes space and may 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 compared to standardized off-board chargers.
6. The power of an on-board charger has practical limits. The more advanced commercial BEV industry has taken an off-board approach for high-capacity charging.
7. Conventional underground mining AC connections might not have an interlock system to prevent the BEV from moving when plugged in.

These issues can probably be resolved when considering a smaller charger (<100 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 and charger size, and charge equipment cooling and protection—all while trying to find space for the charger on the various mobile platforms.

9.4.2 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 16).

9.4.2.1 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 9.4.1.2). The charging system design must meet specific protocol / plug type, or be proprietary and compatible between BEV and charging system.

Several kilometres of travel ways will be developed in an underground mine during its operating life. As such, both the charging method and location of charging installations must be taken into account. For static charging (charging that works only while the BEV is stationary), dedicated and strategically positioned BEV charging locations would be required throughout the mine. Integrating standardized charging interfaces would allow different types of BEVs to charge at the nearest available charging location, negating the need for the BEV to return to a dedicated charger. Static charging may be best-suited to charging mobile BEVs that do not have limited or restricted movements. By comparison, dynamic charging (while the vehicle is moving) would help prevent limited range issues associated with BEVs. Dynamic charging would be better suited

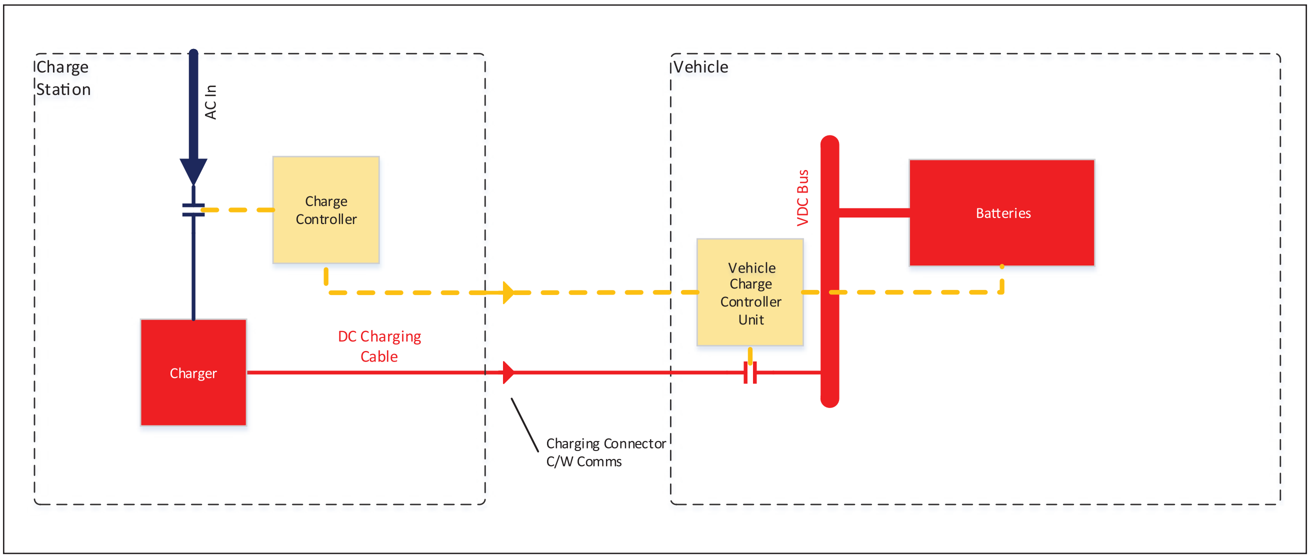


Figure 16. Off-Board Charging Arrangement

to tram haulage scenarios, where the mode of operation is continuous and repetitive.

Regardless of the method chosen, the charger locations should provide for wayside equipment, as well as ease of access for equipment maintenance and inspection. A typical off-board charging arrangement locates wayside equipment such as transformers, charging pads, cooling units and rectification equipment in a fixed enclosure removed from the BEV.

9.4.2.2 Charging interface

9.4.2.2.1 Manually operated connection interface

The power electronics for converting AC line voltage to DC for charging is housed within stationary equipment next to the BEV. Hence, a DC connector is used. Overall, the application of off-board charging in mines is an evolving situation. Ultimately, multiple connectors may be required.

While the charge is taking place, the BEV 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, at up to 80% 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.

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. At least four connector types are in use.

1. More than 10,000 CHAdeMO connectors have been installed to date worldwide (Figure 17). This connector has found widespread acceptance in Japan, 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).

Figure 17. CHAdeMO Connector (reprinted from Kane, 2016)

2. There are two versions of CCSs—Type 1 and Type 2—which differ only in the physical connector. North American automakers favour Type 1 and European automakers favour Type 2 CCSs (Section 9.4.1.2) with two DC pins added (Figure 18). The SAE J1772-based connector (Table 8) is rated for 350 kW with a range of 200–1,000 VDC, while Type 2 is suitable for up to 350 kW (500 A at 1,000 VDC).
3. China has implemented a separate GB/T type connector, capable of 187.5 kW (250 A at 750 VDC; Figure 18).

Figure 18. CCS Type Connectors (reprinted from Phoenix Contact, 2018)

4. 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.

For DC chargers that use a cable and plug to connect to a BEV, 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 CHAdeMO and CCS Type 1 or Type 2 connectors have the following advantages:

- Proven performance in automotive industry
- Locking connector
- Relatively lightweight and manageable
- Easy to maintain
- Readily available spare parts
- Various scenarios can be tested "out of the box" (e.g., insertion / removal testing)

Disadvantages include:

- Automotive connectors are plastic, which is 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

9.4.2.2.1.1 Recommendation for standardization

A standardized, non-proprietary charger interface is vital to control charging cost and complexity. The best way to standardize a charger interface for mining is to use one from the automotive industry. As of now, the CCS is the most widely adopted standard among automotive OEMs and can be adapted for use in mines. It has the following advantages:

- Physical interface and communication protocol are designed to allow a robust and safe connection between the charger and the BEV.
- It is capable of DC-charging up to 1,000 V; other systems can only charge up to about 500 V, which is not enough for large mining BEVs.
- The CCS cable assembly has current ratings up to 200 A, which enables up to 350 kW charging power. Emerging liquid-cooled cable assembly technology will allow higher current values, while keeping cable maneuverability and ease of handling.
- The latest CCS standard enables up to 500 A, for 500 kW charging.
- A new version (CCS 3.0), currently in draft form, will allow for wireless communication, inductive charging, reverse power transfer, and pantographs.

It is not possible to implement either Type 1 or Type 2 CCS world-wide due to availability and certification requirements. We recommend use of the CCS type applicable to your region.

9.4.2.2.1.2 Communication protocol

Communication protocols include controller area network (CAN) or powerline communication (PLC). PLC carries the following benefits:

- It leverages automotive "standard" chargers
- PLC interfaces are available for purchase
- PLC is an established communications framework for BEVs
- Standards IEC 61851-23:2014 and DIN SPEC 70121 (Table 8) are now being chosen as industry standards in the bus and port equipment industries
- Standard SAE J3105 (Table 8) electric vehicle power transfer system using a conductive overhead autoconnect charging device is currently in preparation for release in late 2018 or early 2019.

The parameters to be exchanged between vehicle and changing stations for the CCS can be found in the OEM CCS protocol and at https://charinev.org.

9.4.2.2.2 Automated coupler devices

Automatic charging interfaces are not standard nor interoperable: it is recommended to use the same charging interface OEM for both halves of the interface to ensure safe operation. Characteristics to consider when choosing a connection interface are:

- Rated voltage according to IEC 60664-1:2007 (Table 8) [CAT III, Pollution Degree 3]
- Rated amperage according to IEC 60364-5-52:2009 (Table 8)
- Ingress protection when mated
- Ingress protection when unmated
- Touch protection
- Enclosed vs. exposed contacts (Y/N)
- Sequencing (ground contact is first make, last break, control pilot (CP) is last make first break) (Y/N)
- Wire cross-section
- Number of power contacts
- Number of signal contact
- Misalignment tolerance
- Available configurations (ex top down, bottom up, side)
- Self-cleaning (Y/N)

9.4.2.2.2.1 Pantographs

As an alternative to connector-based charging, pantograph-based systems are being used to charge larger BEVs such as city buses. Pantographs are mechanical linkages connected such that the movement of one arm produces identical movements in a second arm. Some varieties are mounted on board the BEV and extend upwards to make contact with the charger (Figure 19 left). In others, the pantograph is mounted on the infrastructure and extends downward onto charging rails on the roof of the BEV (Figure 19 right). 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) and is expected to increase. Several electric bus and infrastructure manufacturers are developing standardized recommended practices for charging interfaces.

The following principles apply to both bottom-up and top-down pantographs. Of key importance is the compliance according to CCS Mode-4 communication. Therefore, a minimum 4-pole design is required for the contact interface with DC+, DC–, protective earth (PE), and CP for communication and safety purposes.

A pantograph may have a mechanical connection sequence as described in IEC 62196-3:2014, clause 6.7 (Table 8), although it is not required. In the case no contact order can be guaranteed during an unintentional disconnect, IEC 61851-23:2014 (Table 8) stipulates that a risk assessment must show that no dangerous situation will occur. Note: when the connection is made, no voltage is present on the automatic connection devices (International Electrotechnical Commission, 2014c).

Two versions of top-down pantographs are currently on the market: with or without the mechanical connection sequence. In the first version, the charging station applies a signal check making sure all poles are connected. The contact verification assures communication between the BEV and charging station can only begin when all contacts are connected properly. Hence, power transmission can only begin when the system is protected by PE and the BEV cannot move if the pantograph is con-

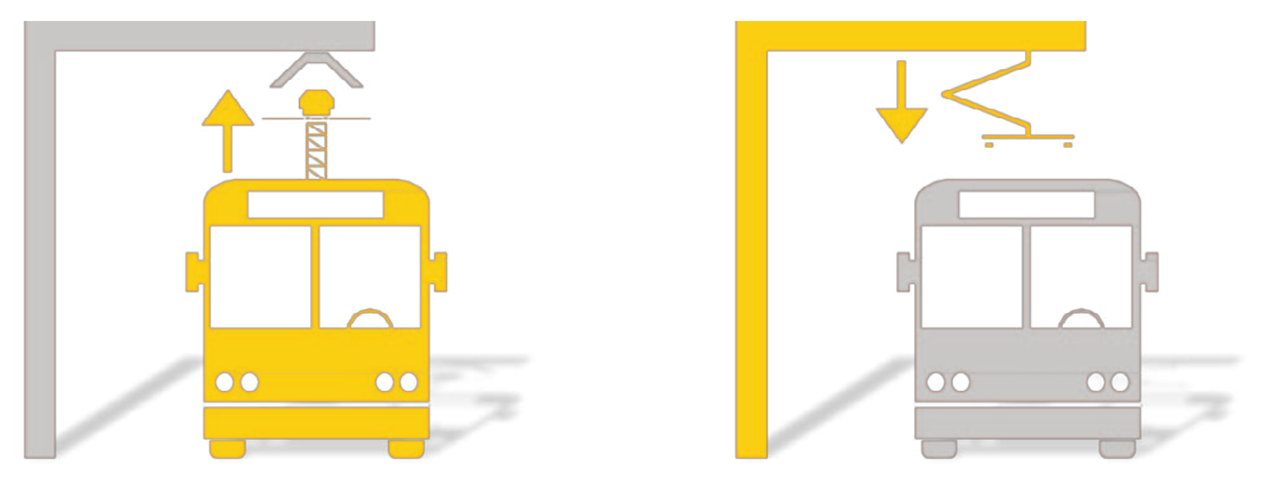


Figure 19. Two Pantograph Interfaces Available and Standardized in SAE J3105 (Table 8)

nected. A very fast disconnection time in case of emergency is required. In the second version, with the connection sequence, there is a variety of interfaces (Figure 20), such as contact cone, contact rails, and contact hood, with different sizes depending on the available space on the roof top of the vehicle.

Another recently adopted option is to use a bottom-up pantograph to charge BEVs from below (Figure 21). The pantograph is installed in the ground on a specific isolated location and the connection interface (modified contact dome) is installed on the chassis / axles of the BEV. The BEV then moves over the pantograph, stopping at the required location. The pantograph moves upward to mate with the interface on the BEV chassis / axles. This high-power charging method is useful when there are limitations on the available space on the BEV roof top for installing contact bars or similar connection interfaces.

High-level communication between the off-board charger and BEV can be done via the CP contact using the PLC protocol or via a wireless interface using an adapted version of the PLC protocol detailed in Section 9.4.2.2.1.2.

For all pantograph charging, IEC 61851-23:2014 (Table 8) specifies a minimum distance of 3 m from the sur-

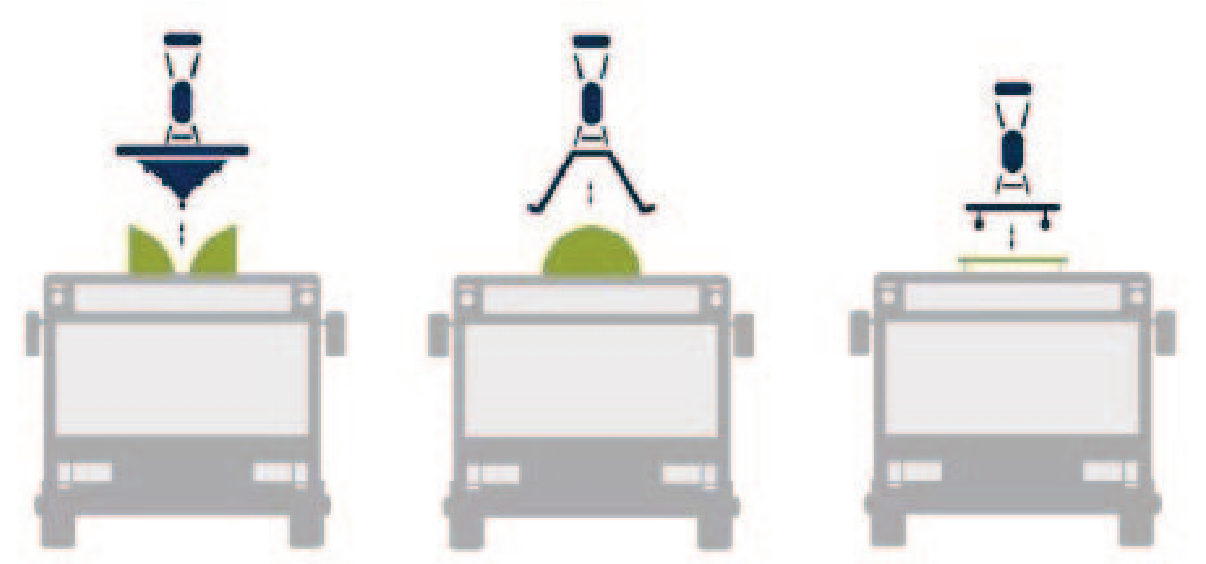


Figure 20. Three Interfaces Available for Top-Down Pantographs with Connection Sequence

Figure 21. Underbody Charging Using a Bottom-Up Pantograph

face on which people stand to any touchable live conductors that are not otherwise protected from human contact.

Advantages of pantograph charging includes:

- Safe automated connection system (no human interaction with power elements)
- Very high power DC charging is permitted (currently up to 600 kW at 1,000 VDC)
- High voltage ratings
- Open-source charging connection systems enabling interoperability among different types of BEV

The disadvantage is that compatibility with an underground mining environment has yet to be evaluated.

9.4.2.2.2.2 Inductive and resonant charging

Inductive charging is similar to pantograph charging but is wireless and eliminates physical contact between the charger and the vehicle. Inductive charging involves energizing a "primary" coil with an oscillating EM field to transfer energy to a "secondary" coil. Resonant charging is a type of inductive charging where primary and secondary coils oscillate at the same resonant frequency, which strongly connects the two coils and does not require precise alignment of the two coils.

A clear benefit to inductive charging is that it is invisible. With no cables, wires, plugs, catenaries, or pantographs to install and deploy, the installation is clean and efficient. Enclosed electrical connections reduce the risk of electrical shorts and shock, and protect the equipment from the corrosion associated with underground mines. In addition, the risk of damage to cables, plugs, and other wayside components is virtually eliminated. Inductive charging also offers an opportunity for automating the charging cycle, because there are no moving parts, and no human interaction is required to connect or disconnect electrical components.

Figure 22. Automated Enclosed Pin and Socket Charging Interface

Currently, two charging methods have been developed for BEVs: stationary and dynamic. Stationary chargers consist of a primary coil that is typically buried underground at a permanent charging base location; the secondary coil is located on the underside of the BEV. Dynamic chargers are similar, but instead of a fixed location for the primary coil, multiple coils are positioned along the route of travel. This allows for seamless and continuous charging while the BEV is in motion. To date, stationary charging is more widely deployed, with several implementations in operation in mass transport systems. Dynamic charging systems are still in their infancy and only experimentally deployed.

9.4.2.2.2.3 Automated enclosed pin and socket

In this type of charging interface, a flexible plug extends from the charging station, plugs into the charging socket installed on the BEV, and initiates charging after a signal is issued (Figure 22). The automated enclosed pin and socket is an interface for rapid, charging systems currently rated up to 1 MW at 1,000 VDC. The enclosed pin and socket interface is fully enclosed and touch-protected with integrated angular and positioning misalignment compensation. It can be installed on the side, front, or back of the BEV. The contacts are inherently self-cleaning.

The entire system is designed to ensure the safety of the operator and other personnel. In all situations—whether or not the system is plugged in—all live parts are out of reach of workers and are protected against accidental contact. The power and signal contacts are released only after the contact carrier has been precisely mechanically connected; the electronic release to start charging is then issued.

9.4.2.3 Off-board proprietary chargers OEMs may choose to develop and supply off-board proprietary chargers 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 multiple BEVs in the fleet throughout the mine, a specific charger for every type of BEV may be 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 maintaining and troubleshooting them.

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.

9.4.2.4 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.

9.4.2.5 Advantages of off-board charging of on-board batteries

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 standard method 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. For standardized interfaces:
    - Those in charge of procuring mobile equipment or charging infrastructure are free to purchase any type of BEV from any OEM.
    - 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.

9.4.2.6 Disadvantages of off-board charging of on-board batteries

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.

9.4.3 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 replaced with a fully charged one (Figure 23). 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 5.1) mean that swapping may be the most viable option if long uphill trips are unavoidable, especially if implementing BEVs in existing mines.

9.4.3.1 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.

9.4.3.2 Battery swapping and charging interface 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.

9.4.3.3 Advantages of battery swapping

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

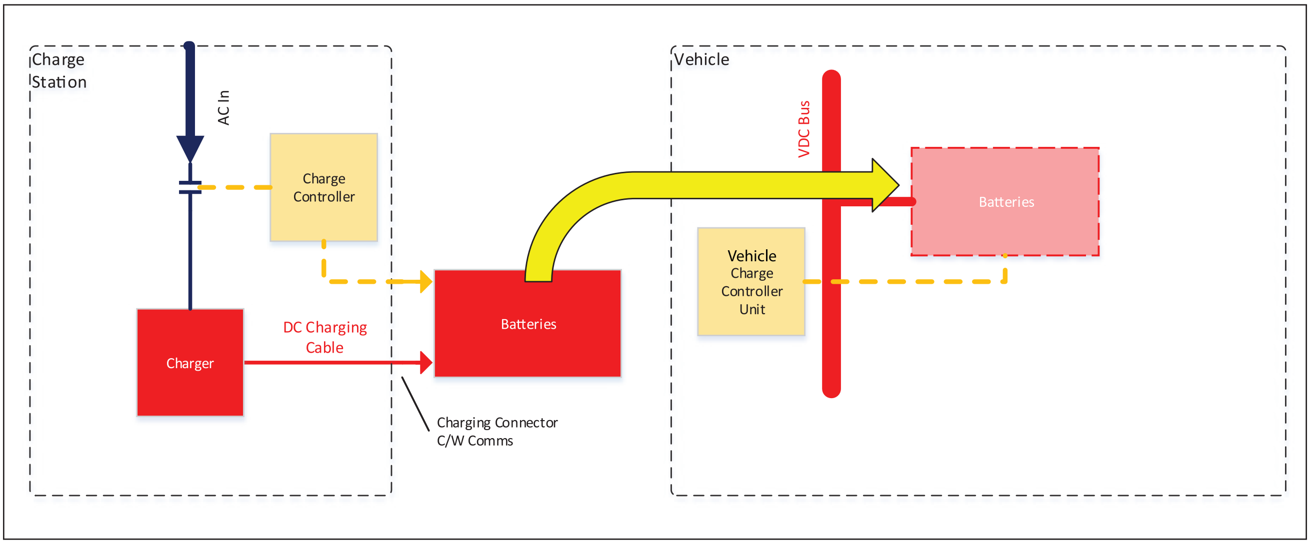


Figure 23. Battery Swapping Arrangement

short periods and the mining schedule arranged so swap-outs occur at predetermined intervals. This will even reduce the cost of ore transport per tonne.

2. 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.

9.4.3.4 Disadvantages of battery swapping

1. Complications are involved in removing the batteries.
    - A manual arrangement (e.g., crane) presents both logistic and safety concerns, given the high frequency of swap-outs.
    - An automated arrangement may suffer from wear and tear in the mining environment, and would require a high level of engineering effort to accommodate all types of BEV.
    - BEV design options could be limited by the need to facilitate battery removal.
2. Fixed infrastructure is required.
    - Dedicated swap-and-charge stations would be needed in strategic locations throughout the mine.
    - The swap-and-charge infrastructure may be large, translating into significantly more mining excavation to house the equipment.
    - 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 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.
    - 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.

9.4.4 Hybrid Charging Method

A combination of on- and off-board charging arrangements can offer some benefits of both (Figure 24). 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.

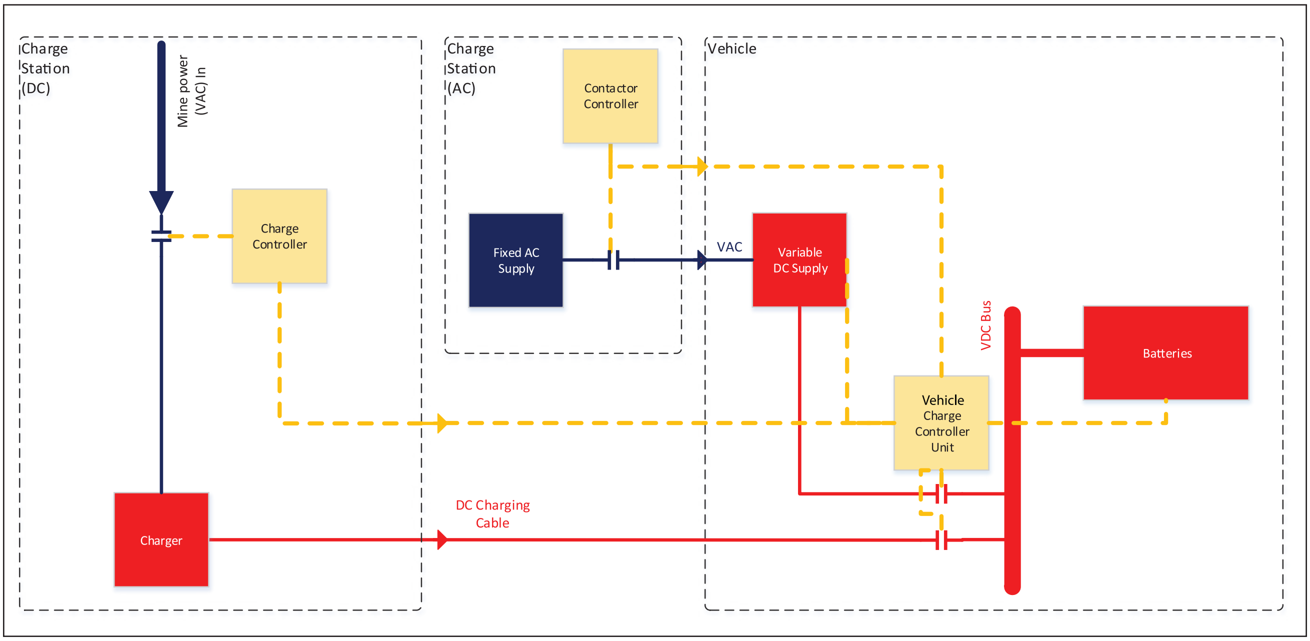


Figure 24. Typical Hybrid Charging Arrangement

9.4.5 Overhead Catenary Systems or Trolley Assist

Trollies have been used in underground mining for many years (especially coal mining). They are typically rail mounted and use AC or DC power fed through cables from overhead catenary systems to move ore and people around the mines. In open pit mining, AC operated haul trucks fed from overhead catenary systems have also been extensively used. The challenge of using a 100% electric truck is the inability of the truck to leave the tracks covered by the trolley system.

A recent iteration, which is not a true hybrid system, uses a pantograph for ramp assist to reduce diesel fuel consumption during the ramp climb. The truck operator aligns the truck with the overhead lines, manually deploys the pantograph, and switches off the diesel; the sequence is reversed toward the end of the climb. The trolley system can be used on the downhill trajectory as well, to inject regenerative energy back into the grid. The technology is moving toward a hybrid system, replacing diesel with battery power, and automating the alignment and the deployment of the pantograph.

9.5 Operation and Controls

9.5.1 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 progress
- Remaining charging time
- Charging complete

9.5.2 Emergency Shutdown Terminals

An E-Stop button 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.

9.6 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, 2018). We suggest implementation of an open communication protocol such as OCPP 2.0.

10. OPERATIONS

10.1 Battery Safety

Relative to the number of rechargeable batteries in active use, LIBs have caused little harm in terms of damage and personal injury. Battery OEMs achieve this high level of safety by adding three layers of protection:

1. Limiting the amount of active material to achieve a workable equilibrium of energy density and safety
2. Including numerous safety mechanisms within the cell
3. Adding an electronic protection circuit in the battery pack

Safety challenges include risks associated with static discharge, faulty chargers, over-discharge, contamination from metal particulates, cold temperature charging, and inappropriate testing. Heat-related battery failures are taken very seriously by OEMs, who typically choose a conservative approach.

The hazards presented by lithium batteries are generally associated with either electrical potential or chemistry. The detailed hazards are discussed in Section 8.3.1. It is the responsibility of OEMs to adequately address the various hazards associated with batteries and to ensure the customer is fully informed of the risks and requirements for handling and operating batteries and battery equipment safely.

Appropriate measures are needed to achieve the mandated safety standard set forth by UL 1642 (see Table 5 and Section 8.2). A nail penetration test that could be tolerated by an older 18650 cell with a capacity of 1.35 Ah would cause an explosion in modern high-density 2.4 Ah cells. As a side note, UL 1642 does not require nail penetration. LIBs are nearing their theoretical energy density limit and battery OEMs are beginning to focus on improving manufacturing methods and increasing safety. For example, a one-in-200,000 failure rate triggered a recall of almost six million lithium-ion packs used in Dell laptops.

10.1.1 Emergency Response and Battery Chemistry

BEVs present a unique risk to owners, operators, workers, maintenance personnel, and safety personnel. Unlike their fossil-fuel counterparts, BEVs can present several battery chemistries, which require special consideration when a BEV is involved in an incident that structurally damages batteries or causes fire on the BEV. LIBs differ from lithium metal batteries and each battery type can have variances in chemistries that prohibit the use of standard fire suppression techniques. Employing the incorrect techniques on a battery chemistry can exacerbate damage to the BEV and potentially put personnel at risk.

Below are key issues that should be considered before any BEV is introduced into the mine:

1. Are the battery chemistry and fire suppression techniques understood for this BEV?
    a. Is the BEV equipped with an appropriate fire extinguisher?
    b. Is the operator trained in the appropriate response to a fire on board?
    c. Are emergency services aware of the proper fire suppression techniques?
    d. Do emergency services have the appropriate training to fight a fire on this BEV?
    e. Do emergency services have the appropriate fire suppression equipment?
2. In mixed fleets, emergency personnel may have to quickly identify the battery chemistry on board a given BEV and choose the appropriate suppression technique.
    a. Can emergency personnel quickly identify the battery chemistry from a distance during an emergency?
    b. Have operators been trained to identify the battery chemistry and any unique responses they should take based on that chemistry?
3. Fires and structural damage will likely lead to a cleanup operation later.
    a. Are mine maintenance personnel aware of the battery chemistry on board the BEV?
    b. Do maintenance personnel have access to the appropriate equipment to clean up after a chemical spill from the BEV.
    c. Do mine maintenance personnel have the proper training to safely effect a cleanup after a battery chemical spill?

In the United States, the National Fire Protection Association has published recommendations for response to BEV fires from LIBs (Long & Blum, 2016), and offers an online course (National Fire Protection Association, 2018).

Table 9. Training requirements for workers associated with BEVs

Role	Electric
Operators	Minimal training for battery user interface and charging
Mechanics	Required for non-electric components (e.g., hydraulic packs)
Electricians	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

10.2 Operator Training

Operation of a BEV differs from a similar machine with a diesel powertrain. Thus, all personnel working with or around a BEV need to be properly trained to fully understand the operational differences, ensure safe practices are used, and identify and avoid potential hazards (Table 9). Operator manuals should be provided by the OEM; additional training options may be available. Typical operational practices that will differ from a diesel equivalent are:

- Daily inspections
- Unit start up
- Brake test procedures
- Performance differences
    - Lower noise levels
    - Higher torque output
    - Higher maximum speed
    - Regenerative braking

Operational differences will exist among OEMs and among BEV models manufactured by a given OEM.

Duty cycle planning is critical for maximizing BEV availability and utilization, because the energy density differs between typical battery chemistries and diesel fuel. Relative to refueling with diesel, BEVs have a shorter tramming range or working time between recharges and take longer to charge or swap the battery. Operators should have an understanding of the energy required to complete a specific task to ensure the charge level is sufficient or make the decision to charge the unit before proceeding. Range estimates from the OEM and training can assist the operator with determining how to proceed.

10.3 Maintenance Personnel Training

When selecting BEVs, the change management for service and repair should be a key consideration. OEMs should be queried about the documentation / training available for their platforms. Table 10 lists standards that could be used to design an appropriate training program.

11. PERFORMANCE STANDARDS

11.1 Introduction

Once the electric mine is operating, data should be collected and analyzed to assess mine performance. 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.

Table 10. Names, topics, and jurisdictions of standards related to BEV operator training. Full standard citations are listed in Section 12.

Recommended Industry Standard	Topic	Jurisdiction	Citation
ISO 14990-1:2016	See Section 15.7 for maintenance manual and service literature, including reduction of electrical hazards while servicing a BEV	International	International Organization for Standardization, 2016a
ISO 20474-1:2017	Specifies appropriate technical measures for eliminating or reducing risks from relevant hazards, hazardous situations, or events during commissioning, operation, and maintenance	International	International Organization for Standardization, 2017d
ISO 8152-1984	Training of mechanics appropriate for earth-moving machinery	International	International Organization for Standardization, 1984
ISO 6750-2005	Specifies the content and gives guidance on the format of operator's manuals for earth-moving machinery	International	International Organization for Standardization, 2005
ISO 7130-2013	Basis for content and methods used for operator training for earth-moving machinery	International	International Organization for Standardization, 2013

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 performance variables that are altered by external factors. 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 travelled. These actions can be defined at fixed distance and / or tailored to specific mining applications. The cycle for a LHD is shown in Figure 25.

For primary haulage equipment (LHDs and haulage trucks) the duty cycle is illustrated in Figures 26 and 27. For the LHD machine duty cycle of load-haul-dump or the truck haulage 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 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 BEV 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 scheduled (calendar) hours without downtime for maintenance or repair (Figure 28). In the case of battery electric equipment, battery charging or swapping hours are considered unavailable hours where the equipment is not available for operation. Equipment utilization is defined as the percentage of time the available equipment worked.

Segment	Grade (%)	Distance (m)	Speed limit (km/h)
A–B	0	20–50	15
B–C	–15	200	5
C–D	–2	70	10

Location	Description
A	Working face
B–C	Haulage decline
D	Crusher

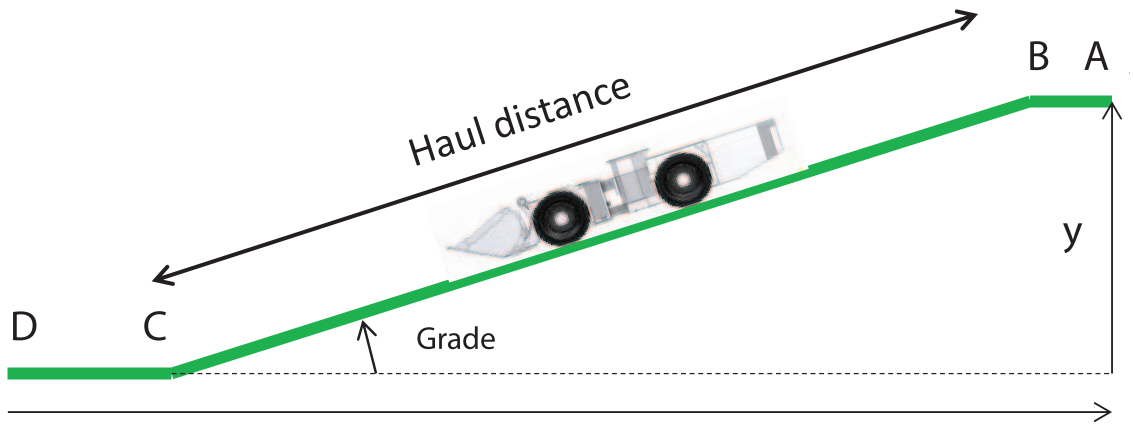


Figure 25. Primary Haulage Cycle: A Load (Muck); B Tram (Haul); C Dump; D Return Tram; E. Repeat

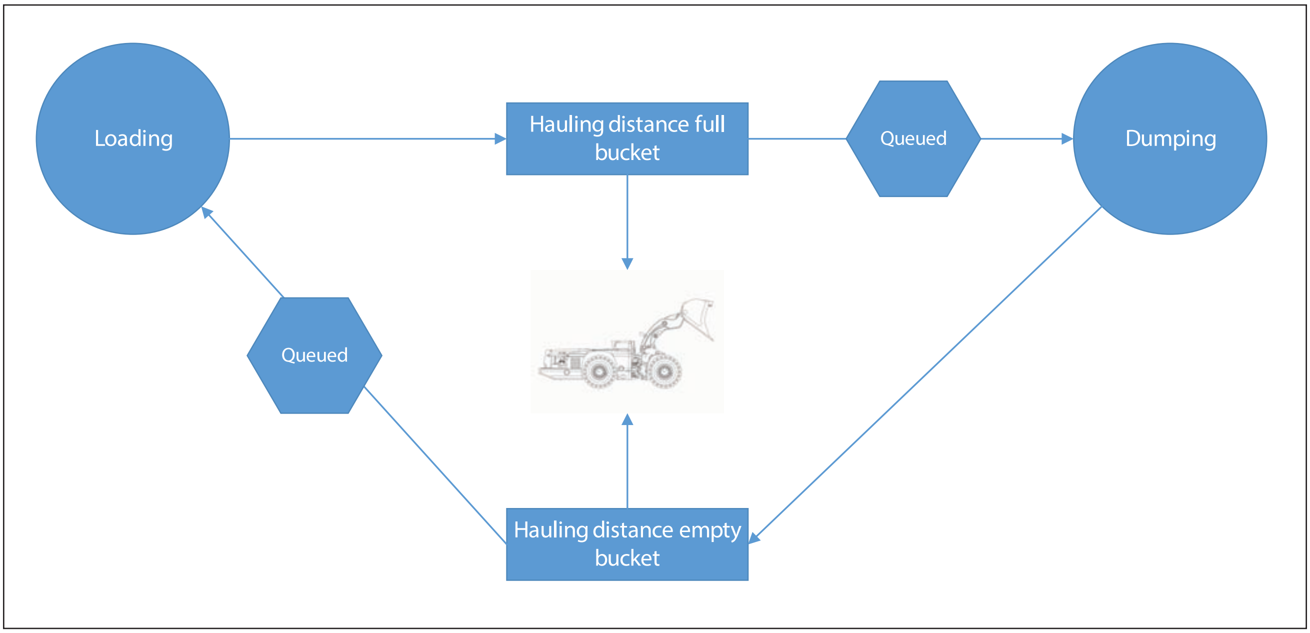


Figure 26. Short Distance Traveled Duty Cycle Scenario for LHD Machines and Trucks

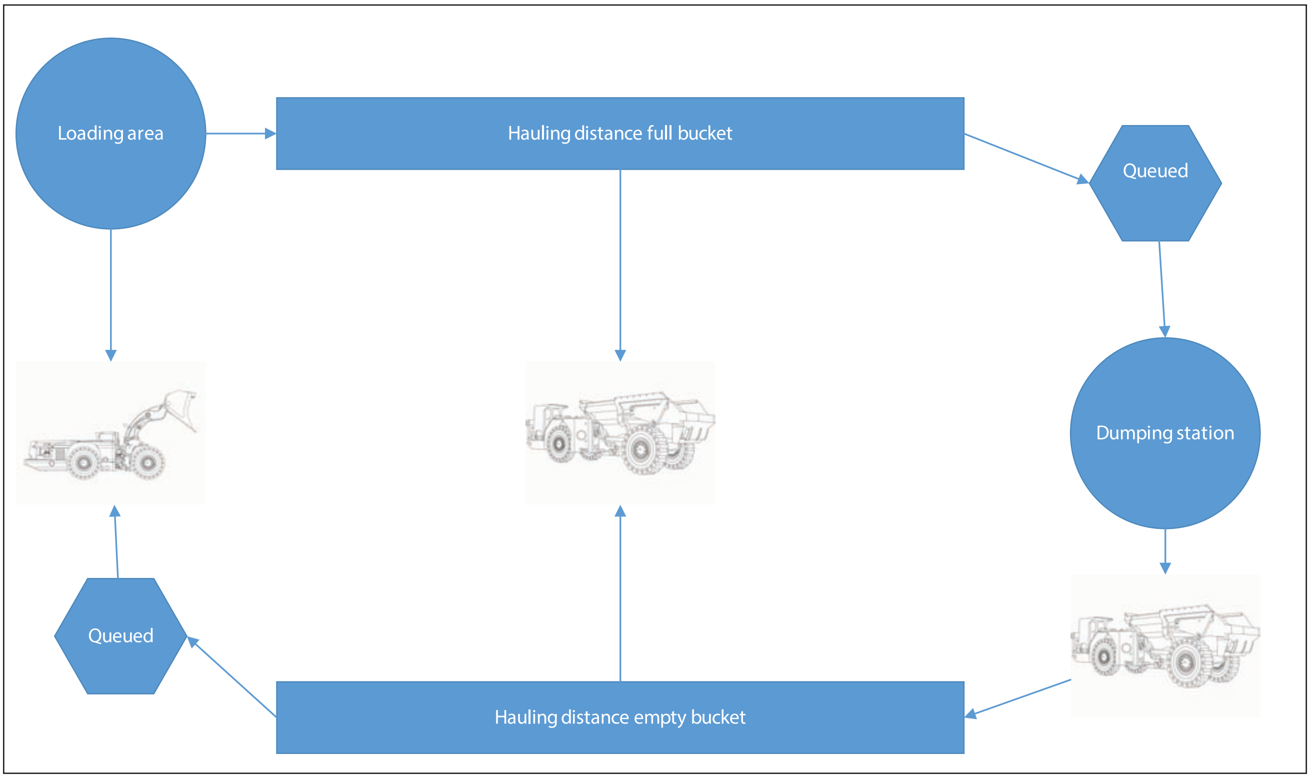


Figure 27. Long Distance Traveled Duty Cycle Scenario for LHD Machines and Trucks

Common definitions and formulas for the parameters are as follows:

Scheduled hours = Calendar hours in a day, month, etc. (168 h/wk)

Available hours = Hours available to operate (includes time between operating shifts)

Unavailable (down) hours = Time unavailable due to breakdown, repair, battery charging, etc.

Operating hours = Hours operated (measured by hour meters on engine and / or BEV system enabled)

$$\text{Available hours} = \text{Scheduled hours} - \text{Down hours} \qquad (1)$$

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

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

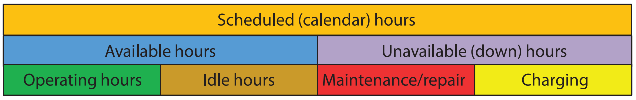


Figure 28. Breakdown of Scheduled Hours

11.2.4 Battery Charge Time

The time required for on-board battery charging or swapping (off-board charging) can be significantly greater than for comparable diesel equipment. If this time period is long, it should be considered down time because the BEV is unavailable to do useful work (Figure 28). BEVs could have lower availability than 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 drive systems (e.g., traction, hydraulic power pack, and auxiliary systems) and the systems would be off during charging, 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 accurately assess 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 field testing with standardized methods and environmental parameters. This will permit mining operators to assess and compare the operational feasibility of the various 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

Table 11. 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 12. 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

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 11 and 12). Also, OEMs should list all operating criteria / assumptions for the performance data communicated, including:

- Road conditions (e.g., rolling resistance [RR] 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 Equipment Performance Assessment

Standardized methods for describing performance for the traction, pump, and auxiliary motors are required to compare battery equipment to diesel 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 s before overheating. The same drive train would be capable of running continuously loaded uphill at full power.
2. Continuous rating should characterize the average energy use 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.

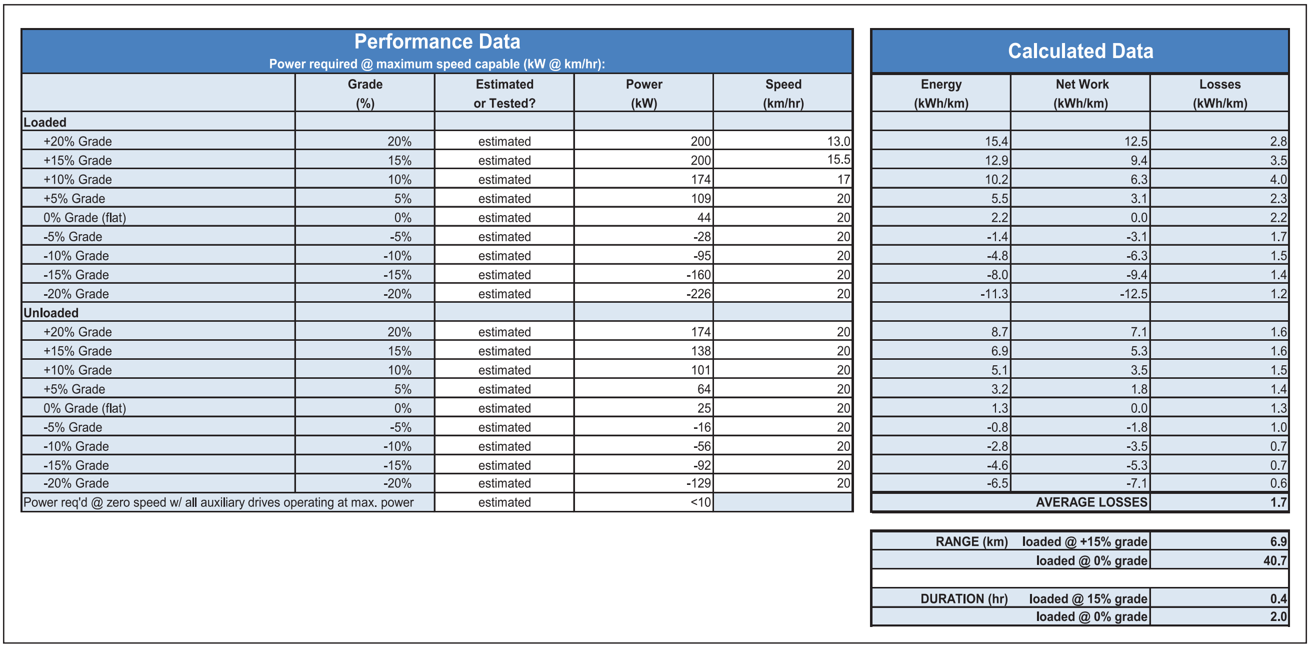
11.3.3 Regenerative Braking Systems

BEVs provide an opportunity to use regenerative braking (Sections 6.2.2 and 7.3). 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 available regenerative braking can greatly influence the range and must be clearly defined in the duty cycle (Section 11.2.1).

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 service brake could be used 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 performance data sheet similar to Figure 29. 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.



Performance Data

Power required @ maximum speed capable (kW @ km/hr):

	Grade (%)	Estimated or Tested?	Power (kW)	Speed (km/hr)
Loaded				
+20% Grade	20%	estimated	200	13.0
+15% Grade	15%	estimated	200	15.5
+10% Grade	10%	estimated	174	17
+5% Grade	5%	estimated	109	20
0% Grade (flat)	0%	estimated	44	20
-5% Grade	-5%	estimated	-28	20
-10% Grade	-10%	estimated	-95	20
-15% Grade	-15%	estimated	-160	20
-20% Grade	-20%	estimated	-226	20
Unloaded				
+20% Grade	20%	estimated	174	20
+15% Grade	15%	estimated	138	20
+10% Grade	10%	estimated	101	20
+5% Grade	5%	estimated	64	20
0% Grade (flat)	0%	estimated	25	20
-5% Grade	-5%	estimated	-16	20
-10% Grade	-10%	estimated	-56	20
-15% Grade	-15%	estimated	-92	20
-20% Grade	-20%	estimated	-129	20
Power req'd @ zero speed w/ all auxiliary drives operating at max. power		estimated	<10	

Calculated Data

Energy (kWh/km)	Net Work (kWh/km)	Losses (kWh/km)
15.4	12.5	2.8
12.9	9.4	3.5
10.2	6.3	4.0
5.5	3.1	2.3
2.2	0.0	2.2
-1.4	-3.1	1.7
-4.8	-6.3	1.5
-8.0	-9.4	1.4
-11.3	-12.5	1.2
8.7	7.1	1.6
6.9	5.3	1.6
5.1	3.5	1.5
3.2	1.8	1.4
1.3	0.0	1.3
-0.8	-1.8	1.0
-2.8	-3.5	0.7
-4.6	-5.3	0.7
-6.5	-7.1	0.6
	AVERAGE LOSSES	**1.7**

RANGE (km)	**loaded @ +15% grade**	**6.9**
	loaded @ 0% grade	**40.7**
DURATION (hr)	**loaded @ 15% grade**	**0.4**
	loaded @ 0% grade	**2.0**

Figure 29. Typical Performance Data Sheet

For basic grade performance data, 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.

11.3.5 Impact of Tires on BEV Performance

When comparing the performance of BEVs, the type of tires on the BEV and the road surface over which the BEV is moving are key factors to consider. In an underground mine, battery energy is used for driving, running auxiliary systems (e.g., cooling/ heating, lights) and to power various processes (mucking, dumping, spraying, drilling, etc.). In particular, the trackless rubber-tired truck-loader haulage systems used to transport fragmented material from the production area to the desired location draw significant energy from the battery during driving to overcome resistive forces such as RR and climbing force. The RR is defined as the force acting on a vehicle caused by the interaction between the tires and the road surface impeding its free rolling. It can significantly impact BEV performance (speed, autonomy, productivity) and should be considered during standard performance measurement tests.

The RR depends on the road surface type (paved or unpaved) and roughness conditions (the presence of irregularities, bumps, mud, snow, etc.) and tire type (bias ply, radial) and condition (inflation pressure, treads, material composition, temperature). These parameters will influence the energy required from the battery to perform a specific duty cycle. For softer surfaces, both bias ply and radial tires yield a similar RR (e.g., surfaces C–H in Table 13). However, when the road surface is harder, radial tires—though more expensive—yield a lower RR than bias-ply tires (surfaces A and B in Table 13) and are preferred for haulage equipment. Moreover, radial tires have tougher overall construction than bias-ply tires, providing a longer life and smoother ride. Overall, radial tires used on hard surfaces consume less energy and have a lower life cycle cost than bias tires. However, bias tires are generally a better choice for loading applications (loaders, scoop trams) because they have stronger and tougher sidewalls, providing more stability when loads are carried up high.

Methods to measure the RR provided by a tire type include:

- Measurement on drums in laboratory
- Specially equipped trailers for measurement on road
- Coastdown measurement on road
- Pulling test on a surface road during which the pull force to move a vehicle at slow speed is measured

RR is usually expressed in terms of percent road grade or in terms of resistance force as a percentage of the gross vehicle weight. For example, a vehicle travelling with 10% RR on a horizontal surface must overcome equivalent resistance to a truck travelling up a 10% grade with no RR. A RR of 2.5–3.0% is often considered for modelling the energy consumption of a rubber tired haulage system used underground, assuming that haulage drift / decline is generally unpaved (compacted crushed rock as surface layer).

11.3.6 Heat Generation

Diesel units produce significantly more heat, but more importantly, produce harmful emissions that must be diluted to safe levels for human occupancy underground through high fresh air ventilation flow rates (see Sections 5 and 6.6). The ventilation requirements in a diesel mine are relatively easy to calculate by summing known engine emissions, and are often legislated based on total diesel power (m^3/s per kW) in the fleet. The total required fresh air ventilation flow to dilute diesel exhaust gasses is usually sufficient to control the heat generated as well, and the mine engineer does not usually need to consider this heat

Table 13. Expected rolling resistance (RR) factors for various road conditions and two tire types (adapted from Caterpillar, 2018)

Roadway condition	**RR (%)**	
	Bias tires	**Radial tires**
Surface A: Hard and smooth; concrete, cold asphalt or dirt surface; no tire penetration or flexing	1.5	1.2
Surface B: Firm, smooth and rolling; dirt or light surfacing; flexes slightly under load; watered; maintained	3.0	2.5
Surface C: Dirt, rutted; flexes under load; 25 mm tire penetration or flexing; no water; little maintenance	4.0	4.0
Surface D: Dirt, rutted; flexes under load; 50 mm tire penetration or flexing; no water; little maintenance	5.0	5.0
Surface E: Dirt, rutted, soft under travel; 100 mm tire penetration or flexing; no stabilization; no maintenance	8.0	8.0
Surface F: Loose sand or gravel; 150 mm tire penetration or flexing	10	10
Surface G: Dirt, rutted, soft under travel; 200 mm tire penetration or flexing; no stabilization; no maintenance	14	14
Surface H: Very soft mud, rutted; 300 mm tire penetration; no flexing	20	20

source when sizing ventilation and refrigeration system requirements.

In an electric mine, these emissions do not exist, and although less heat is generated, heat is the only "contaminant" that must be assessed to determine ventilation and refrigeration requirements for the electric mobile equipment fleet. The quantity of heat produced depends on continually varying duties of each unit, and the efficiency of each machine's drivetrain and charging system. Some key concepts to understand are:

1. Energy cannot be created or destroyed, it changes from one form to another (The (Law of Conservation of Energy).
2. If a vehicle does not raise a load, no potential energy is stored and all energy transmitted from the battery (kWh) is lost as heat.
3. Zero net work is done if a vehicle returns to its starting point, and the net energy consumed to move the machine is lost as heat. Energy used to move material to a higher elevation is put into the potential energy of that material.
4. Zero net work is done if a vehicle moves a load on level ground, and all energy consumed is lost as heat.
5. Vehicles require energy to overcome drivetrain, RR and auxiliary loads. This energy is ultimately converted to heat.

The concepts above indicate that a solid understanding is required of the duty of each unit. In addition, the efficiency of each unit must be known or estimated to determine average heat generated during a typical operation. These heat values can then be summed for the fleet during a typical operating shift to determine the ventilation flow rates and / or refrigeration requirements for the mine.

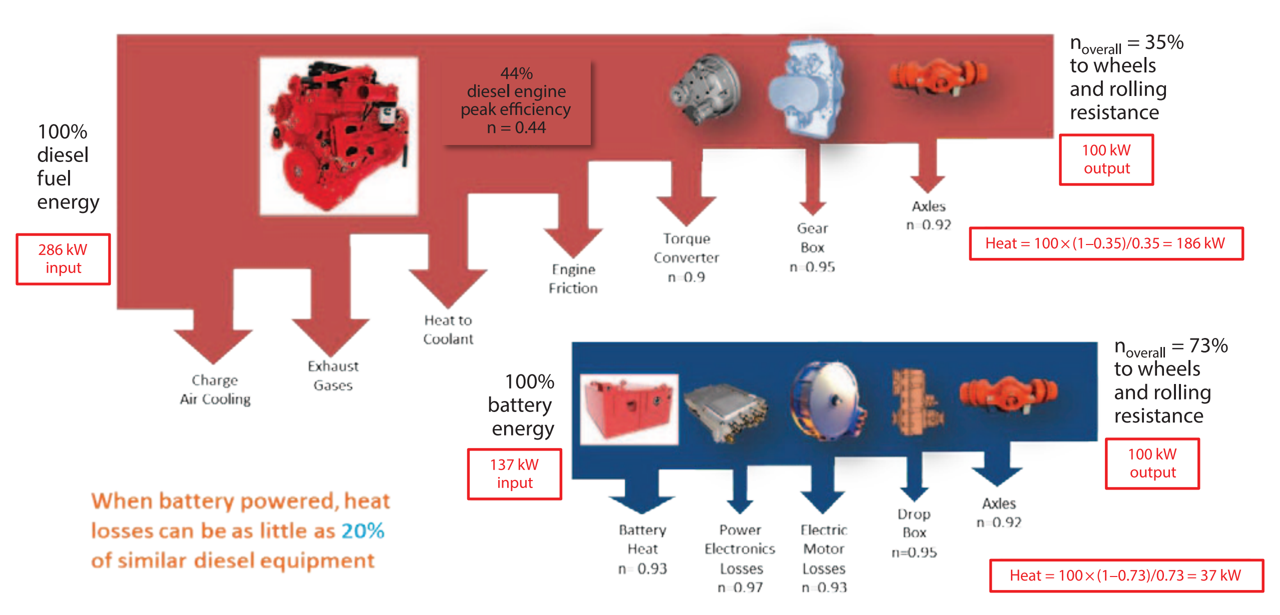


Figure 30. Comparison of Heat Generation and Efficiency between Diesel And Battery Electric Vehicles

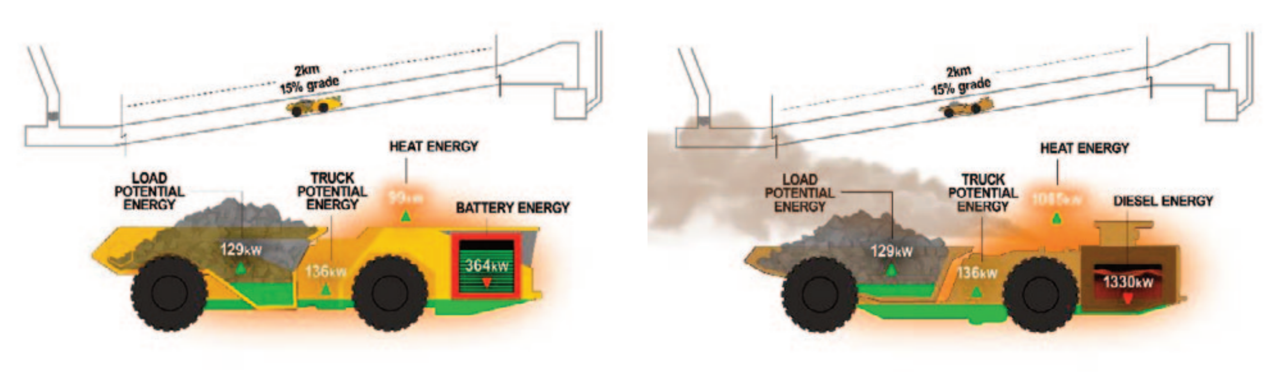


Figure 31. Energy Flow for a Battery Electric (left) and Diesel Truck (right)

A benefit of BEVs over diesel vehicles is the significant improvement in efficiency and reduction in heat generation (Section 5.1). Figure 30 compares the efficiencies of each component of the respective drives and the resulting heat losses. Heat generation from a BEV can be as little as 20% of similar diesel equipment.

An additional advantage of BEVs is that during braking and down ramp operation, most systems are able to channel kinetic energy to charge the battery. This regenerative braking (Sections 6.2.2, 7.3, and 11.3.3) allows the machine to recoup some portion the energy put into the potential energy of the BEV mass at a higher elevation. The total heat generation can be significantly affected, since not only are the kinetic and potential energy not lost as heat, but they are re-used to continue operation. Since a diesel vehicle does not have a large energy storage reservoir (battery), this energy is lost as heat and cannot be re-used.

Consider the energy flow when a BEV or diesel truck is hauling a load up a ramp (Figure 31). When driving up-ramp with a load, battery energy is flowing to the losses as heat. It is also used to accelerate the mass of the vehicle and load:

$$\text{Kinetic energy} = 0.5 \times \text{mass} \times \text{velocity}^2 \tag{4}$$

Battery energy is also used to move the combined mass higher in elevation, which is stored as potential energy:

$$\begin{gathered}\text{Potential energy} = \\ \text{mass} \times \text{acceleration due to gravity} \times \text{height}\end{gathered} \tag{5}$$

During deceleration, the kinetic energy can be returned to the battery to be re-used for the next acceleration. When travelling down-ramp empty, some portion of the potential energy of the vehicle can be captured and put back into the battery pack. The only heat generated is thus the net energy consumed by the battery pack, minus the potential energy of any material left at a higher elevation. The potential energy of a 30 tonne mass that is 2 km up a 17% ramp is approximately 27.4 kWh.

If you consider hauling down-ramp loaded with waste rock for backfill, materials, or other payload, the potential energy of that load can act as an additional energy source (other than energy from the charger). This can effectively provide fuel for the truck while performing a needed service.

The current challenge facing the mine engineer is to obtain a reliable source of information related to heat generation for specific machines. It is important that OEMs test each unit to determine the electrical energy consumed (or power required) on various load conditions and ramp grades. By subtracting mechanical work done for each of these cases, the overall losses and heat generation can be determined.

It is suggested that OEMs develop performance data sheets (e.g., Figure 29) that present the overall efficiency of the BEV in terms of losses. These losses equate to the average heat generation (measured in kW or kWh/km) and can be used to determine ventilation and refrigeration requirements.

11.4 Battery Performance

11.4.1 Performance

A key performance criterion of interest to mine operators is the run-time of the 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 operate 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 (Section 8.3). 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 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 14.

11.4.2 Specifications

Battery specifications are important to understand 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 15 and performance charts similar to examples shown in Table 16 and Figure 32.

Table 14. Battery performance parameters

Parameter	Consideration
Voltage and current	Are there practical / safety limits that should be enforced?
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?
Capacity	kWh nameplate—does not represent "useable" energy Beginning vs. end of life Warrantied kWh delivered? Number of cycles? Ah throughput? "Electric brake reserve"—how much battery energy needs to be reserved for downhill navigation? (Section 11.4.2)

Table 15. 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 (% per month)	
	Memory effect (Y/N)	
	Cooling time (h)	
	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 16. 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

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 17.

11.6 Machine 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 18.

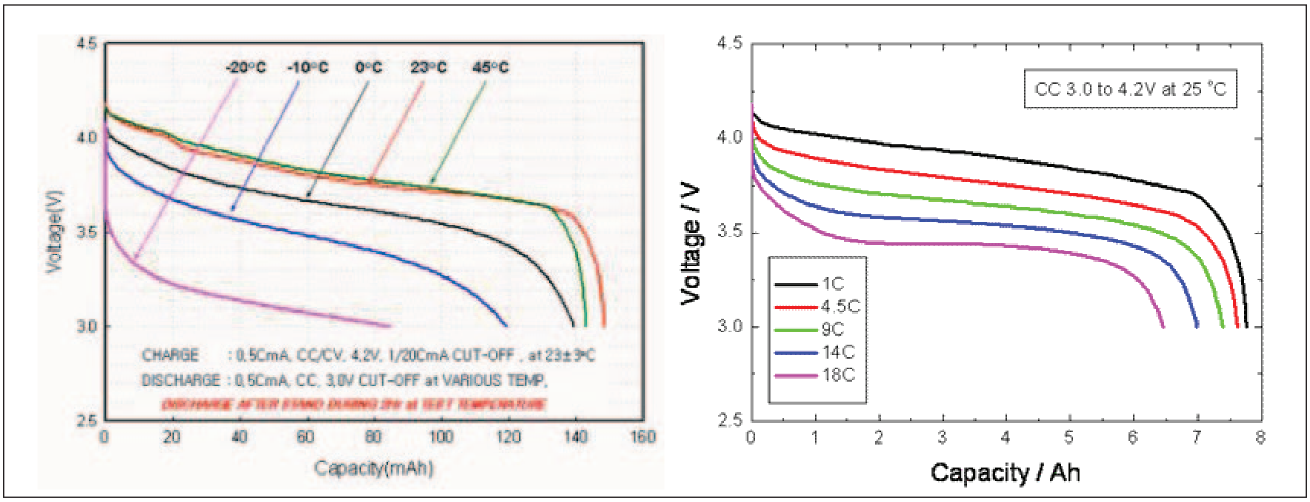


Figure 32. Examples of Battery Performance Charts

Table 17. Battery charger requirements

Description	**Details (to be completed by OEM)**
Dimensions (L × W × H)	
Weight (kg)	
Operating temperature (°C) and humidity	
Input range (maximum 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 18. Machine performance data (example)

Description	**Details from mining company**
Equipment type	40 tonne haul truck
Heading size	5 m × 5 m (helps define box capacity limitations)
Ore density	2.1 t/m^3 broken density (for calculation of actual load)
Profile description	2 km haul, up-hill carry, 15% average grade, peak of 17%
Seat time	8 h/shift, 2 shifts/day
Objective	Haul 800 t/day
Description	**Examples of outputs by OEM**
Loads per charge	4
Loads per shift	14
Swaps per shift	3 (8 min each, for 24 min total per shift)
Capacity per load	40 t
Speed (km/h)	10 loaded (up), 12 unloaded (down)
Cycle time (minutes)	32 min (22 min tram with 10 min for load, dump and traffic)
Production capability	560 t/shift 1,120 t/day
Production objective	met with one truck – 320 t/day margin

12. RESOURCES, REFERENCES, AND RECOMMENDED READING

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