GLOBAL MINING GUIDELINES GROUP

GMG

RECOMMENDED PRACTICES FOR BATTERY ELECTRIC VEHICLES IN UNDERGROUND MINING

VERSION 3 - PUBLISHED 2022
THE ELECTRIC MINE WORKING GROUP

Global Mining Guidelines Group (GMG)

ABOUT GMG

The Global Mining Guidelines Group (GMG) is a network of representatives from mining companies, original equipment manufacturers (OEMs), original technology manufacturers (OTMs), research organizations and academics, consultants, regulators, and industry associations around the world who collaborate to tackle challenges facing our industry. GMG aims to accelerate the improvement of mining performance, safety, and sustainability by enabling the mining industry to collaborate and share expertise and lessons learned that result in the creation of guidelines, such as this one, that address common industry challenges.

Interested in participating or have feedback to share? GMG is an open platform, and everyone with interest and expertise in the subject matter covered can participate. Participants from GMG member companies have the opportunity to assume leadership roles. Please contact GMG at info@gmggroup.org for more information about participating or to provide feedback on this guideline.

GMG was formed out of the Surface Mining Association for Research and Technology (SMART) group as part of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) and with the support of other Global Mineral Professionals Alliance (GMPA) members.

GMG is an independent, industry-led organization.

ABOUT GMG GUIDELINES

GMG guidelines are peer-reviewed documents that describe good practices, guide on the implementation and adoption of new technologies, and/or develop industry alignment. They are the product of industry-wide collaboration based on experience and lessons learned. The guidance aims to help readers identify key considerations, good practices, and questions to ask on the topic covered and enable operational improvements for safe, sustainable, and productive mines.

Once the guideline is reviewed and accepted by the project group steering committee, working group members peer review and GMG members within the working group vote to approve draft documents prior to their approval by the GMG Board of Directors.

GMG guidelines are intended to provide general guidance only, recognizing that every situation will be different. Use of these guidelines is entirely voluntary and how they are applied is the responsibility of the user. These guidelines do not replace or alter standards or any other national, state, or local governmental statutes, laws, regulations, ordinances, or appropriate technical expertise and other requirements. While the guidelines are developed and reviewed by participants across the mining industry, they do not necessarily represent the views of all of the participating organizations and their accuracy and completeness are not guaranteed. See the disclaimer on p. iv for further detail.

RELATED GMG DOCUMENTS

While guidelines are the primary output of GMG Working Groups, GMG also produces documents that supplement guidelines. These include:

- White papers: Educational or foundational documents that provide broad knowledge and identify further reading on a topic that is new to or not well-understood in the industry. These documents are reviewed throughout development and editing but do not undergo the working group review and voting process as guidelines do. These projects can lead to guideline development.
- Reports: Outcomes of outreach, industry research, and events can be presented in reports and can inform the priorities for developing industry guidance.
- Landscapes: Reviews of ongoing related work by other organizations on a key topic. These aim to provide the industry with an idea of what exists and prevent duplication of effort.
- Case studies/other examples and tools: These documents aim to share knowledge and provide examples for the benefit of the broader industry and supplement GMG guidelines.

RELATIONSHIP TO STANDARDS

GMG guidelines are not standards and should not be treated as such. The guidelines can be used to assist the mining community with practices to improve their operations and/or implement new technologies. They aim to supplement, not replace, existing standards, regulations, and company policies. Guidelines can also be a first step in identifying common and successful practices and feed into standardization efforts. GMG does not develop standards but does participate in standardization efforts through partnerships.

CREDITS

The following organizations and individuals were involved in the preparation of these guidelines at various stages including content definition, content generation, and review. Please note that the guidelines do not necessarily represent the views of the organizations listed below.

Project Group

Battery Electric Vehicles v3

Working Group

The Electric Mine Working Group

Project Leaders

Troy Charsley, Hatch
Craig Harris, Glencore
Maarten Van Koppen, MacLean Engineering

Project Steering Committee

Thiago Amaral, Siemens
Nic Beutler, ABB
Nick Gardner, Vale
Anders Lindkvist, Epiroc
Brian Huff, Sandvik
Luke Mahony, Vale
David Rababy, Stäubli
Sasan Khajavi, Stäubli
Michel Serres, BBA
Paul Summers, Miller Technology

Content Contributors

Franck Boudreault, Epiroc
Denis Caron, Agnico Eagle
James Coe, Komatsu
Jean-Francois Couillard, Adria Power Systems
Jerry Davis, Komatsu
Fred Delabbio, Strategy Focused Innovation Pty Ltd
Kyle Ferguson, Siemens
Adrianus (Adrian) Halim,
Luleå University of Technology, Sweden
Jacques Jodouin, Jodouin Mine Ventilation
Leonard Kaskiw, Government of Saskatchewan, Canada
Dan Laing, Stantec
John Le, Natural Resources Canada
Kevin Lueschow, Caterpillar
Mike Mayhew, Mayhew Performance
Kent Mei, TestSafe
Shawn Samuels, Epiroc
Doug Turnbull
Jayde Webb, South32
Larry Widdifield, Elphinstone
Jian Zhao, Meglab

PARTICIPATING ORGANIZATIONS INVOLVED IN THE PREPARATION OF THESE GUIDELINES (VERSION 3)

3ME Technology, ABB, Adria Power Systems, Agnico Eagle, Artisan Vehicles, AusIMM, BBA, BESTECH, Boliden, Byrnecut, Caterpillar, China Mining Products Safety Approval and Certification Center, Clean Air Metals, EELO Solutions, Elphinstone, Epiroc, General Dynamics, Glencore, Government of Saskatchewan, Hatch, Hermann Paus Maschinenfabrik, Jodouin Mine Ventilation, Komatsu, Kovatera, Luleå University of Technology, MacLean Engineering, Mayhew Performance, Meglab, Miller Technology, MineRP, Mining Plus, Natural Resources Canada, Northern Light Technologies, Northern Star Resource, Nutrien, Rio Tinto, Saminco, Sandvik, Schunk, Sibanye-Stillwater, Siemens, South 32, Stantec, Staubli, Strategy Focused Innovation,Tembo e-LV, TestSafe, Vale, Verdant Holdings

PUBLICATION INFORMATION

This guideline version is a significant revision of the previous version. While the base content is similar, sections have been rewritten, removed, reordered, and revised. See Section 1.4 for further detail on the types of updates made.

Guideline Number: GMG07-EM-2022
Version Three Published: 2022-06-23
Version Two Published (in partnership with CMIC): 2018-05-11
Version One Published (in partnership with CMIC): 2017-08-28
Revision Cycle: 2 years

DOCUMENT USAGE NOTICE

© Global Mining Guidelines Group. Some rights reserved.

GMG is an open platform. This document can be used, copied, and shared, aside from the exceptions listed below.

Exceptions to the above:

- Third-party materials: If you wish to reuse material from this work that is attributed to a third party, such as tables, quotations, figures, or images, it is your responsibility to determine whether permission is needed for that reuse and to obtain permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned content in the work is the responsibility of the user.
- GMG branding and logo: The use of the GMG logo and associated branding without permission is not permitted. To request permission, please contact GMG (see the contact information below).
- Translation: If you translate the work, include the following disclaimer: "This translation was not produced by GMG. GMG is not responsible for the content or accuracy of this translation."
- Derivatives: Adaptations, modifications, expansions, or other derivatives of this guideline without permission are not permitted. To request permission, please contact GMG (see the contact information below).
- Sales: While you can use this guideline to provide guidance in commercial settings, selling this guideline is not permitted.

Should you use, copy, or share this document, you must clearly identify that the content comes from GMG by citing it. The citation must include all the information in the recommended citation below.

Recommended citation: Recommended Practices for Battery Electric Vehicles in Underground Mining — Version 3 (GMG07-EM-2022). Global Mining Guidelines Group (2022).

CONTACT INFORMATION

Global Mining Guidelines Group
info@gmggroup.org
gmggroup.org

DISCLAIMER

This publication contains general guidance only and does not replace or alter requirements of any national, state, or local governmental statutes, laws, regulations, ordinances, or appropriate technical expertise and other requirements. Although reasonable precautions have been taken to verify the information contained in this publication as of the date of publication, it is being distributed without warranty of any kind, either express or implied. This document has been prepared with the input of various Global Mining Guidelines Group (GMG) members and other participants from the industry, but the guidelines do not necessarily represent the views of GMG and the organizations involved in the preparation of these guidelines. Use of GMG guidelines is entirely voluntary. The responsibility for the interpretation and use of this publication lies with the user (who should not assume that it is error-free or that it will be suitable for the user's purpose). GMG and the organizations involved in the preparation of these guidelines assume no responsibility whatsoever for errors or omissions in this publication or in other source materials that are referenced by this publication, and expressly disclaim the same. GMG expressly disclaims any responsibility related to determination or implementation of any management practice. In no event shall GMG (including its members, partners, staff, contributors, reviewers, or editors to this publication) be liable for damages or losses of any kind, however arising, from the use of or reliance on this document, or implementation of any plan, policy, guidance, or decision, or the like, based on this general guidance. GMG (including its members, partners, staff, contributors, reviewers, or editors to this publication) also disclaims any liability of any nature whatsoever, whether under equity, common law, tort, contract, estoppel, negligence, strict liability, or any other theory, for any direct, incidental, special, punitive, consequential, or indirect damages arising from or related to the use of or reliance on this document. GMG (including its members, partners, staff, contributors, reviewers, or editors to this publication) is not responsible for, and make no representation(s) about, the content or reliability of linked websites, and linking should not be taken as endorsement of any kind. We have no control over the availability of linked pages and accept no responsibility for them. The mention of specific entities, individuals, source materials, trade names, or commercial processes in this publication does not constitute endorsement by GMG (including its members, partners, staff, contributors, reviewers, or editors to this publication). In addition, the designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of GMG (including its members, partners, staff, contributors, reviewers, or editors to this publication) on the legal status of any country, territory, city, or area or of its authorities, or concerning delimitation of any frontiers or boundaries. This disclaimer should be construed in accordance with the laws of Canada.

EXECUTIVE SUMMARY

This guideline describes recommended practices for the use of battery electric vehicles (BEVs) in underground mining. Its intent is to provide guidance and an overall discussion about the benefits, drawbacks, and planning needed to design and implement a BEV fleet within an existing or new mine.

BUSINESS CASE

Converting to an all-electric mine offers many advantages. However, like all new adaptions, there are challenges associated with the integration of a new system or technology.

Topic	Core considerations
Revenue	Differences in productivity and performance to accommodate BEVs. Potential development of traditionally uneconomic orebodies.
Capital cost	Electrical infrastructure costs on-site to distribute power to operations. Mine design related changes such as quantity and size of drifts and shafts.
Operating cost	Choices in charging/fuelling strategies can drive operating costs. Typically, lower ventilation-related costs.
Health, safety, environment, and community	Improved workplace conditions in terms of vibration, noise, air quality, temperature, and humidity. Reduced environmental emissions.

MINE DESIGN AND OPERATIONS

Important considerations for mine design and operations include accommodation of changes associated with charging methods, ventilation and cooling, mine cycle and schedules, risks, and maintenance and operations requirements.

Topic	Core considerations
Mine layout and infrastructure	Key operational constraints of BEVs include a limited range, time required to charge and swap batteries, estimated cycle times, and distances from charging stations. Planning and scheduling changes are required to integrate BEV constraints and conform to plans. Factors associated with the ore/waste handling system that should be considered include the OEM requirements, grade of the ore, and site conditions. Regenerative braking while tramming downhill should be assessed with the operational profile of the BEV to optimally place charging locations and reduce the charging times.
Maintenance areas	Typical designs optimizing shop workflow with repair bays and specialty bays for welding, tire handling, or lube are still desirable. Space and infrastructure to test, maintain, discharge, charge, and store batteries is needed.
Personnel movement and parking	Shaft access: Movement between the shaft station and BEV need to be considered to accommodate charging and personnel safety. Ramp access: Group travelling is highly recommended for efficiency.
Mobile electric equipment	Design and operational considerations vary for different equipment types. For example, tethered equipment typically requires accommodations for the cable, while trucks might focus more on regenerative braking.

Charging infrastructure	A general layout of the mine and its development is required to design charging infrastructure. Overall considerations include: • Operational constraints such as appropriate infrastructure and cost implications of charging methods (on-board charging, off-board charging, battery swapping, or alternatives) • Mining cycle and schedules for charge time versus operating time
– Charging philosophy	The starting point should be the mine layout and the operational map of the vehicles. Considerations include: • Standardization of charging methods and connection interfaces versus hybrid or mixed methods depending on fleet size and equipment types • Haulage routing and scheduling and methods of accommodating long uphill haulage
– Charging station layout	Considerations include the physical environment, the preparation of the charging area for installation, spacing and parking, battery swapping, power distribution, and fast charging.
– Opportunity charging	Charging occurs during the natural or process-imposed downtime of the BEV and does not reduce productivity.
Ventilation and cooling	Ventilation and cooling system designs in an electric mine consider temperature, dust, and air velocity parameters, however because of the elimination of diesel, some aspects of the criteria associated with DPM regulations might not be required. Local regulations should be consulted for specifics. Key considerations during the development of the ventilation design and planning include: • Sizing, placement, and number of airways • Heat • Blast gas clearing • Monitoring • Controlled recirculation • Presence of strata gases (e.g., radon) • Dust
– Heat load	Despite heat reduction in BEVs, there are still factors that contribute to the heat generated including efficiency, usage work rate, and gradient. Heat from other sources (e.g., summer surface climate, auto compression, wall rock, groundwater) also contributes to the overall heat load. These sources are not dependent on the type of the equipment used, but they should still be managed by the mine ventilation and cooling system.
– Dust	Consideration of ventilation air volumes can contribute to removal of dust contaminants, however, it can also create new risks if the air volume is too high/low.
– Radon	If significants amounts of radon are produced from the orebody, then large air volumes might be required to manage it. Additionally, mines with radon typically needs to excavate more ventilation shafts than mines that do not have radon.
Battery and fire safety	BEVs can present several battery chemistries and battery designs, which require specific consideration when involved in an incident that structurally damages batteries or causes a fire on the BEV. Emergency response is a key consideration in case a battery fire occurs. The OEM needs to supply the fire scenarios and specialized safety measures dependent on the types of batteries they provide. General guidance includes: • Consider equipment health and condition monitoring plans to support prevention and early detection. • Refuge stations should be planned in the production and development levels in each mining zone to mitigate risks. • Make sure battery chemistry and fire suppression techniques for the BEV are understood. Consult local regulations for specifics. • In mixed fleets, emergency personnel might have to quickly identify the battery chemistry on-board a given BEV and choose the appropriate suppression technique. • Fires and structural damage can potentially lead to a cleanup operation.
Training	All personnel working with or around a BEV should be properly trained. Depending on the role of personnel, different training requirements are needed (e.g., operators might need to be trained in new inspection criteria, emergency procedures, test procedures, or equipment start-up procedures).

Risk assessment	The risk assessment is a key step in operational planning, the following should be considered: • Financial risks (e.g., increased infrastructure capital expense, early battery replacement) • Production risks (e.g., discharged vehicle recovery, production rate impact) • Health and safety risks (e.g., fire/explosion, electric shock, arcing fault) • Environmental risks (e.g., worn battery skulls toxic to environment)

BATTERY ELECTRIC VEHICLE DESIGN

The design of a BEV comprises several different components and should integrate a strong relationship between the design of the electric motor and other BEV components.

Topic	Core considerations
Braking system	Rheostatic braking should have the capacity to dissipate the braking power. Regenerative braking using batteries requires a reserve battery capacity in which energy can be returned to the battery by the supply line. The battery system and traction motor affect regenerative brake limits and shortfalls. An electric traction motor requires an electric supply to hold a vehicle stationary against an external force.
High-voltage direct current (HVDC) electrical system	System modeling, fault current, and arc flash studies should be conducted to confirm the BEV is designed in accordance with electrical principles, that all electrical components are able to withstand the full range of voltage and current to which they can be subjected, and to estimate the incident energy that would be present in the event of an arcing fault. Overcurrent and overage protection are crucial to prevent injury, battery fire, and irreparable damage to the BEV. Insulation and ground fault monitoring systems should monitor high-voltage energy between the electrical system and vehicle chassis, and they should alert personnel if there is a risk of shock.
Low-voltage and control systems	Low-voltage distribution and control systems should be designed to avoid operating modes or sequences that can cause a fault condition or component failure leading to a hazard. A high-voltage interlock loop should be used to prevent direct exposure of high voltage. An emergency stop function should be included in the BEV design. Operator interfaces should include visible and audible signals to advise personnel that a vehicle is underway and if there are critical safety alerts. Risk assessments should include the identification and analysis of any firmware/software controls that directly impact critical functions or identified risks.
Maintenance and service areas on the equipment	Battery packs can require special procedures to bring down overall potential to an acceptable service value. Design of maintenance and service areas should consider the arrangement and handling of components, enclosures and covers, service areas, and signage and labels. OEMs should provide recommended schedules and procedures for inspecting and maintaining BEVs and their components.
Electrical and radio interference	BEVs should be designed to conform to electromagnetic compatibility standards to avoid affecting nearby equipment or devices.
Drivetrain	Motor setup for an underground BEV depend on the vehicle type and size. Key specifics to consider with BEVs include wheel or axle motors, hydraulic pumps, and the cooling system.
Shock and vibration	BEVs should be designed to meet shock and vibration profiles that align with the anticipated use environment.
Fire safety	The system should be designed to help make sure that a vehicle fire does not propagate to the battery.

ENERGY STORAGE SYSTEMS (BATTERIES)

The rechargeable energy storage system (battery) is central to BEV operations. The battery storage capacity (energy density) limits the range that the BEV can travel or perform its task between charges and is the main obstacle when considering implementation, particularly in mining due to high vehicle weight and energy requirements.

	Topic	Core considerations
FUNCTIONAL REQUIREMENTS	Battery management system (BMS)	The BMS should be integrated into the BEV design and be able to communicate with the charging infrastructure and emergency shutdown subsystems.
	Thermal management and testing	The BMS monitors the temperature, which can prevent hazardous situations and damage to the battery in the event of high temperature conditions.
	Cycle performance and battery life	Conditions and usage profiles should be defined, and additional testing procedures can be applied to the systems to better estimate battery life.
	Automatic shutdown	The automatic shutdown of the system should be designed and tested to comply with relevant safety standards.
	System enclosure	Protection specifications such as venting requirements and designated lifting points for the battery system enclosure are supplied by the OEM.
	Extreme temperature considerations	Because batteries have optimal temperature ranges, it is key to minimize the amount of time they are outside that range to maximize the performance.
	Storage	Storage conditions such as temperature range and component life with and without state of charge (SOC) or state of health checks should be fully defined by the battery manufacturer or OEM.
	End-of-life	Batteries should be decommissioned and disposed of according to local laws or can be rebuilt by qualified personnel for extended use. Three options to consider are disposal as waste, recycling, and second life.
SAFETY REQUIREMENTS	Hazard conditions	Key hazard conditions include charging or discharging at low temperature, over- and undervoltage, overloading, overtemperature, external and internal short-circuit, external heating, chemical reactions, mechanical crush, shock, penetration, and rupture of a cell resulting in liquid or flammable/toxic gas release. Key methods of preventing hazard conditions include: • Sensor data that notify the BEV control unit to take corrective action and cause an alarm if the battery temperature is out of safe operating range • Appropriate battery mechanical protection, usage, and handling
	Fire hazards	Batteries can be compromised due to physical or hazard conditions that lead to an increase in temperature, resulting in thermal runaway and the production of flammable and toxic gases. Carbon monoxide and hydrogen fluoride are especially dangerous risks in underground fires as they can both spread through mining zones.
	Fire suppression and response	Early detection of a battery fire and an effective fire responsive practice can prevent incidents from becoming more serious. The suppressant should have the ability to contain and cool the battery fire and prevent reignition.
	Transportation	Transportation regulations should be consulted to transport battery systems, BEVs, and spare parts containing batteries safely. Damaged or suspect batteries should be transported according to applicable regulations.

CHARGING SYSTEMS AND METHODS

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. Some mine operations will depend on the availability of fully charged batteries; therefore, sufficient design in the charging system is crucial.

	Topic	Core considerations	
CHARGING SYSTEMS	Safety considerations	The charger should be compliant with regional safety standards and should be designed to prevent shock, mechanical hazards, and avoid physical risk.	
	Charger installation	The charger should be compatible with the energy storage type and chemistry in use, rated for the appropriate charging rate, and compatible with different conditions.	
	Incoming power systems	A power study is recommended for the overall underground electrical design along with several other considerations.	
	Operation and controls	Two key components are operator control visibility and emergency shutdown terminals.	
	Communications and monitoring	These systems should be capable of load management, reporting and monitoring of charging infrastructure, notification of events to relevant staff, and prioritization of which vehicle is charged and at what power level (if load or charging configuration constraints are imposed).	
CHARGING METHODS	On-board charging	Can be a good option for mixed fleets or if additional fixed infrastructure is not feasible.	
		Advantages • No separate charging infrastructure • Charging location flexibility • Reduced downtime	*Disadvantages* • Additional weight and size of chargers can limit battery size and range • Design challenges with accommodating the charger on the equipment • Charging equipment exposed to harsh conditions • Lower power capacity
	Off-board charging of on-board batteries	Can be a good option if high-power chargers are required or if operating a large BEV fleet.	
		Advantages • Less equipment onboard • Size and weight reduction • Chargers in contaminant-free locations • BEVs can share chargers	*Disadvantages* • Fixed infrastructure required (especially challenging in large mines) • BEV needs to move to a specific location to charge • High power capable batteries needed
	Off-board charging of off-board batteries (swapping)	Can be a good option if long uphill trips are required, especially if implementing BEVs in existing mines. This method also shares some advantages with off-board charging of on-board batteries.	
		Advantages • Potentially improve productivity (e.g., not out of service to charge) • Lower charger power required • Some reduction in infrastructure requirements (e.g., designated parking)	*Disadvantages* • Additional infrastructure/mechanisms needed either on– or off-board to facilitate swapping (removal and mounting) • More chargers and batteries required • Less flexibility and can be difficult to standardize • Battery inventory management can be challenging
	Hybrid	A combination of on- and off-board charging arrangements can offer some benefits of both.	
	Off-board proprietary chargers	OEMs can choose to develop and supply off-board proprietary chargers. Trials and small-scale implementations could benefit from the simplicity of not needing to handle multiple systems.	

TYPES OF CHARGING AND CONNECTION INTERFACES

Charging and connection interfaces can vary depending on the chosen charging method, region, and equipment design. Standardization is recommended as much as possible.

Topic	Core considerations
On-board charging from alternating current (AC) supply interface	Connector types are defined by IEC 62196-1, IEC 62196-2, and IEC 62196-3 and vary depending on region. This interface is typically used for low-rate charging and consideration. It is recommended to use a long and easily replaceable output cable.
Off-board charging interface, manually operated	Multiple DC connectors are typically required. The two versions of combined charging systems CCS-Type 1/Combo 1 and Type 2/Combo 2 are most widely used in mining. For chargers using a cable to connect to a BEV, taking precautions to prevent damage is recommended.
Off-board charging interface, automated	The potential benefits over manual interfaces include saving time, greater comfort, reliability, and future-readiness. Potential disadvantages include a higher initial cost, greater weight, and higher complexity due to the number of components. Types of automated charging interfaces include infrastructure mounted pantograph systems, enclosed pin and socket systems, and inductive systems.
Battery swapping and charging interface	It is recommended to use a durable connector to accommodate many connection/disconnection cycles. The connector needs to be able to handle the high power requirements for batteries to be charged at very rapid rates. Interoperability is a key challenge.

PERFORMANCE STANDARDS

Once the electric mine is operating, data should be collected and analyzed to assess mine performance. The duty cycle can be more complex than it is for diesel vehicles because how the equipment gets the energy (i.e., the charging method) needs to be evaluated. Battery charging and swapping can also affect availability and utilization.

Topic	Core considerations
Equipment performance	Equipment performance parameters include general requirements, equipment performance assessment, regenerative braking systems, specifications, impact of tires and road surface on BEV performance, and heat generation. Key performance considerations include: • The ability to achieve the same or better output for a given duty cycle as a comparable diesel unit • The energy requirements to perform the duty cycle and number of such cycles the battery is capable of before charging is required • The time required to charge or swap the battery
Battery performance	Considerations include determining battery life, cycle life, state of health, charge and discharge rates, depth of discharge (DOD), estimation, and charging temperature estimation.
Charger performance	It is important to understand the timing of charging, the location of charging stations, and the potential opportunity for charging considerations based on mine power availability.

ABBREVIATIONS

AC	Alternating Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
CCS	Combined Charging System
CO	Carbon Monoxide
DC	Direct Current
DOD	Depth of Discharge
DPM	Diesel Particulate Matter
FLA	Full Load Amperage
GHG	Greenhouse Gas
HF	Hydrogen Fluoride
HRR	Heat Release Rate
HVDC	High-Voltage Direct Current
HVIL	High-Voltage Interlock Loop
IDLH	Immediately Dangerous to Life of Health
KPI	Key Performance Indicator
LHD	Load-Haul-Dump
LIB	Lithium-Ion Battery
LMO	Lithium-Ion Manganese Oxide
LTO	Lithium Titanate
NO_2	Nitrogen Dioxide
NCA	Lithium Nickel-Cobalt-Aluminum Oxide
NMC	Lithium-Manganese-Cobalt-Oxide
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OWHS	Ore/Waste Handling System
PE	Protective Earth
PPE	Personal Protective Equipment
SEI	Solid Electrolyte Interface
SO_2	Sulphur Dioxide
SOC	State of Charge
TLV	Threshold Limit Value
TWA	Time Weighted Average
VDC	Variable Direct Current

TABLE OF CONTENTS

EXECUTIVE SUMMARY v

Business Case v

Mine Design and Operations v

Battery Electric Vehicle Design vii

Energy Storage Systems (Batteries) viii

Charging Systems and Methods viii

Types of Charging and Connection Interfaces x

Performance Standards x

ABBREVIATIONS xi

TABLE OF CONTENTS xii

1. INTRODUCTION 6

1.1 Purpose and Audience 6

1.2 Scope 6

1.3 Navigating this Guideline 7

1.3.1 Finding Similar Content 8

1.3.2 Finding Safety Content 8

1.4 Description of Updates in Version Three 8

2. GENERAL BACKGROUND 9

2.1 Advantages of Battery Electric Versus Diesel Vehicles 9

2.2 Disadvantages of Battery Electric Versus Diesel Vehicles 10

3. BUSINESS CASE 11

3.1 Introduction 11

3.2 Revenue 12

3.2.1 Performance and Productivity 12

3.2.2 Traditionally Uneconomic Orebodies 13

3.3 Capital Costs Considerations 13

3.3.1 Overall Infrastructure Considerations 13

3.3.2 Vehicle and Battery Assets 13
3.3.3 Ventilation and Cooling Infrastructure 13
3.3.4 Electrical Infrastructure and Power Distribution 14
3.3.5 Layout 14

3.4 Operating Cost Considerations 14
3.4.1 Overall Energy Requirements and Costs 14
3.4.2 Differences in Ventilation-Related Operating Costs 15
3.4.3 Maintenance Costs 15

3.5 Health, Safety, Environment, and Community 16
3.5.1 Working Environment 16
3.5.2 Training 16
3.5.3 Sustainability and Community Acceptance 16

4. MINE DESIGN AND OPERATIONS 17

4.1 Introduction 17

4.2 Mine Layout and Infrastructure 18
4.2.1 Ore/Waste Handling System 18
4.2.2 Regenerative Braking and Ramp Design 19

4.3 Maintenance Areas 20

4.4 Personnel Movement and Parking 20
4.4.1 Shaft Access 20
4.4.2 Ramp Access 20

4.5 Mobile Electric Equipment 21
4.5.1 Charge-While-Operating Equipment Group (Tethered) 21
4.5.2 Trucks 22
4.5.3 LHD Machines 22
4.5.4 Auxiliary Vehicles 22

4.6 Charging Infrastructure 22
4.6.1 Design Prerequisites 23
4.6.2 Charging Philosophy 23
4.6.3 Charger Diversity 25
4.6.4 Opportunity Charging 25
4.6.5 Charging Station Layout 25
4.6.6 Charging System Operation and Maintenance 28

4.7 Ventilation and Cooling 28
4.7.1 Determining Air Volume 30
4.7.2 Regulations 30

4.7.3 Equipment Fleet 31
4.7.4 Heat Load 31
4.7.5 Dust 33
4.7.6 Radon 33
4.7.7 Developing the Ventilation Design and Plan 33

4.8 Battery and Fire Safety 35
4.8.1 Refuge Station Considerations 36
4.8.2 Emergency Response and Battery Fires 36

4.9 Training 36
4.9.1 Operator Training 37
4.9.2 Maintenance Personnel Training 38

4.10 Risk Assessment 38
4.10.1 Financial, Production, Health and Safety, and Environmental Risks 39
4.10.2 Risk Management Tools 41

5. BATTERY ELECTRIC VEHICLE DESIGN 44

5.1 Introduction 44

5.2 Braking System 45

5.3 HVDC Electrical System 46
5.3.1 Direct Current (DC) System Architecture 46
5.3.2 System Modelling, Fault Current, and Arc Flash 47
5.3.3 Overcurrent and Overvoltage Protection 48
5.3.4 Insulation/Ground Fault Monitoring 48
5.3.5 Isolation and Service Disconnect 48
5.3.6 Traction Drive and Motor 48
5.3.7 Auxiliary Drives and Motors 49
5.3.8 DC/DC Conversion 49
5.3.9 Battery Charger Integration 49

5.4 Low Voltage and Control System 49
5.4.1 Low-Voltage Distribution and Control 49
5.4.2 High-Voltage Interlock Loop (HVIL) 49
5.4.3 Master Disconnect 49
5.4.4 Emergency Stop 49
5.4.5 Operator Interfaces 51
5.4.6 Software/Firmware Risk Assessment 51
5.4.7 Remote Control 51

5.5 Electrical and Radio Interference 52

5.6 Drivetrain 52

5.7 Fire Safety 52

5.8 Shock and Vibration 52

5.9 Maintenance and Service Areas on the Equipment 53

5.10 Standards Cited in this Section 54

6. ENERGY STORAGE SYSTEMS (BATTERIES) 59

6.1 Introduction 59

6.2 Background on Battery Types 59

6.3 Functional Requirements 60

6.3.1 Battery Management System 60
6.3.2 Accessibility, Maintenance, and Service 60
6.3.3 Thermal Management and Testing 60
6.3.4 Cycle Performance and Battery Life 61
6.3.5 Automatic Shutdown 61
6.3.6 System Enclosure 61
6.3.7 Extreme Temperature Considerations 61
6.3.8 Storage 62
6.3.9 End-of-Life 62

6.4 Safety Requirements 63

6.4.1 Hazard Conditions: Causes and Effects 63
6.4.2 Hazard Condition Monitoring, Prevention, and Mitigation 64
6.4.3 LIB Chemistry and Thermal Runaway 65
6.4.4 Fire Hazards and Suppression 65
6.4.5 Transportation 67

6.5 Standards Cited in this Section 67

7. CHARGING SYSTEMS AND METHODS 71

7.1 Introduction 71

7.2 Safety Considerations 72

7.3 Charger Installation 72

7.4 Incoming Power System 72

7.5 Types of Charging Methods 72
7.5.1 On-Board Charging 73
7.5.2 Off-Board Charging of On-Board Batteries 74
7.5.3 Off-Board Charging of Off-Board Batteries (Battery Swapping) 75
7.5.4 Hybrid Charging Method 76
7.5.5 Off-Board Proprietary Chargers 77
7.5.6 Alternative Charging Systems and Equipment Types 77

7.6 Operation and Controls 78
7.6.1 Operator Control Visibility and Lighting 78
7.6.2 Emergency Stop 78

7.7 Communications and Monitoring 78

7.8 Standards Cited in this Section 78

8. TYPES OF CHARGING AND CONNECTION INTERFACES 80

8.1 Introduction 80

8.2 On-Board Charging from Alternating Current (AC) Supply Interface 81

8.3 Off-Board Charging Interface 82
8.3.1 Manually Operated Connection Interface 82
8.3.2 Automated Connection Interfaces 83

8.4 Battery Swapping and Charging Interface 87
8.4.1 Durability 88
8.4.2 Power 88
8.4.3 Interoperability 89

8.5 Standards Cited in this Section 89

9. PERFORMANCE STANDARDS 92

9.1 Introduction 92

9.2 Definitions 92
9.2.1 Duty Cycle 92
9.2.2 Availability and Utilization 93
9.2.3 Idle/Queued Periods 93
9.2.4 Battery Charge Time 93

9.3 Equipment Performance 94
9.3.1 General Requirements 94
9.3.2 Equipment Performance Assessment 95

9.3.3 Regenerative Braking Systems 95
9.3.4 Specifications 95
9.3.5 Considering Production and Service Requirements 95
9.3.6 Impact of Tires and Road Surface on BEV Performance 96
9.3.7 Heat Generation 96

9.4 Battery Performance 99
9.4.1 Performance 99
9.4.2 Specifications 100

9.5 Charger Performance 100
9.5.1 Performance 100
9.5.2 Specifications 100

10. FUTURE WORK 102

GLOSSARY 103

APPENDIX A. REFERENCE CASES 105

APPENDIX B. EXPLOSION PROTECTION FOR GASSY MINES 106

APPENDIX C. BEV GENERAL INFORMATON FORM (EXAMPLE) 108

1. INTRODUCTION

This guideline describes recommended practices for the use of battery electric vehicles (BEVs) in underground mining. This is the third version of this guideline and was updated collaboratively by participants from the GMG Electric Mine Working Group.

1.1 PURPOSE AND AUDIENCE

The intent of this guideline is to provide guidance and an overall discussion about the benefits, drawbacks, and planning requirements for designing and implementing a BEV fleet within an existing or new mine. It aims to strike an appropriate balance between standardization and innovation by providing key considerations, questions to ask, and guidance on where to look for further information.

While it is not a standard, this guideline is intended to enable discussions between mining companies and mining vehicle original equipment manufacturers (OEMs). It can also be used by OEMs, battery manufacturers, and charger manufacturers in research and development efforts.

This guideline aims to assist mining companies with operating a fleet of BEVs. It leverages and references existing standards and guidelines, including those that have some applicability from automotive, electrical, automation, and other industries. At the same time, this guideline should not be an obstacle to innovation for OEMs.

Note on the current standards landscape

Standardization for mining BEVs is still in its early stages. Some existing standards identified as applicable to mining BEVs are IEC 60204-1, IEC 60204-11, ISO 14990 Series, and Canadian standards CSA M421-16 and CSA M424. While there are many established BEV standards from other industries that can be useful references, they are not always directly applicable in mining settings.

1.2 SCOPE

This guideline is intended to cover a wide range of considerations and practices around using BEVs and to support the adoption of them, but its scope is not intended to be exhaustive. It is intended to support, not replace, the advice of qualified experts and relevant standards and regulations. The table below gives a general summary of in scope and out of scope items.

Table 1.1 Summary of Guideline Scope

Category	In scope	Out of scope
Equipment	• Mobile, trackless, fully battery electric vehicles in mining • Mixed fleets and fully electric fleets • Lithium-ion batteries (LIBs) are the reference technology for BEVs in mines, although other chemistries are considered	• In-depth guidance on other types of electric equipment (e.g., trolley assist systems, tethered systems), though some high-level considerations are covered • Hybrid diesel/electric vehicles
Mining contexts	• Underground mining • Greenfield and brownfield operations	• Surface mining, except in some instances as a point of comparison
Global applicability	• Should be able to be used by mining companies and OEMs globally while acknowledging that regional differences exist in terms of local regulatory frameworks	• Specific or prescriptive information about regional regulatory frameworks
Relationship to standards	• Leverages and references existing standards and guidelines	• Prescriptive information or information to replace existing standards

1.3 NAVIGATING THIS GUIDELINE

This guideline is structured into eight sections arranged in a logical sequence for an underground operation considering going electric. These topics and their primary audiences (indicated in blue text below) are briefly summarized below. Please note that the guidance can still be helpful to many beyond the identified primary audience.

General Background (Section 2): Provides a general overview of the advantages and disadvantages of BEVs in underground mining when compared to diesel vehicles.

Those starting to think about BEVs as an option.

Business Case (Section 3): Includes guidance on building the business case and considering the scope for implementation. It expands on key considerations including revenue, capital cost, operating cost, health and safety, and environment and community.

Those at the conceptual stage looking to understand and develop the business case for BEVs.

Mine Design and Operations (Section 4): Includes guidance and considerations about mine design and operations to accommodate BEVs. It includes information on mine layout and infrastructure, other electric equipment, personnel movement and tracking, charging infrastructure, ventilation and cooling, training, risk assessment, and related safety concerns such as fire risk and emergency response.

Mine planners and engineers, operations and maintenance teams, training personnel, and health and safety personnel.

Battery Electric Vehicle Design (Section 5): Includes information about the systems and components of a BEV and their design and use, including braking systems, electrical systems, control systems, and drivetrain as well as considerations around shock and vibration, safety, and electrical and radio interference.

Mine operations, maintenance, and project teams to understand the systems from both a procurement/specification aspect as well as OEMs for use in research and development and enabling communications with customers.

Energy Storage Systems (Section 6): Includes information about the components, use, and design of energy storage systems (batteries), including information on functional requirements such as accessibility and service, thermal management, cycle performance and battery life, and safety requirements such as hazard conditions and safe transportation.

Mine operations and maintenance teams to understand the systems, and battery manufacturers for use in research and development and enabling communications with customers.

Charging Systems and Methods (Section 7): Includes information on charging systems and methods, including safety considerations, incoming power system, types of charging methods, and operations and controls.

Mine operations and maintenance teams to understand the systems and charger manufacturers for use in research and development and enabling communications with customers.

Types of Charging and Connection Interfaces (Section 8): Covers types of charging and connection interfaces including on-board charging, off-board charging interfaces (manually connected, conductive automated connection, proprietary chargers, and standardized interfaces), and battery swapping interfaces.

Mine operations and maintenance teams to understand the systems and charger manufacturers and OEMs for use in research and development and enabling communications with customers.

Performance Standards (Section 9): Describes the type of data and information required to assess the capabilities of BEVs and define typical performance parameters and requirements to enable the development of standard approaches.

Mine management and operations personnel to understand performance requirements and capabilities to enable improvements and OEMs to understand industry needs and requirements.

1.3.1 Finding Similar Content

Many topics covered in this guideline are covered from different perspectives across the sections. For example, regenerative braking is covered in Section 4 from a design and layout perspective, Section 5 from a BEV design perspective, and Section 9 from a performance standards perspective. Text boxes (see example on the right) are included throughout the guideline to indicate some other sections with related content.

- Example cross reference box

1.3.2 Finding Safety Content

While some sections of this guideline focus primarily on safety (indicated in their titles), guidance related to safety is prominent throughout many other sections as well. A navigation box is included in the introduction of each of the longer sections featuring information on where to find safety-related information.

⚠ Section navigations include lines of blue text preceded by a safety warning symbol to identify the type of safety-related information covered in the section.

1.4 DESCRIPTION OF UPDATES IN VERSION THREE

Version three of this guideline is a significant revision from version two, published in 2018. While much of the content is similar, the entire guideline has been revised to bring it up to date with the current information available on BEVs in mining and to improve its quality. Some key content updates include:

- New and expanded content on safety, risk, and emergency response, particularly in reference to battery fires.
- New and expanded content on maintenance, including maintenance area design, charging system and maintenance, training, and equipment maintenance and service area design.
- Expanded content on developing the business case.
- New sections on automated connection interfaces.

Because electric mining technology is evolving rapidly, the approach to updating this guideline was to keep it general enough that it would not go out of date. Some notes and examples related to emerging technologies and practices are considered, but very specific guidance is avoided as much as possible. Because BEVs are more widely adopted globally than they were in 2018, additional clarity was also added throughout to recommend the user consult the regulations and standards relevant to their local jurisdictions. Further work was also done to make sure the guidance is non-prescriptive and can be applied broadly.

Structural improvements are another key feature of version three. The introductions to each section have been restructured to improve navigation and to highlight key areas of the section that cover safety. Other key structural changes include:

- The General Background, Business Case, and BEV Design sections were internally restructured for clarity.
- The Mine Design and Operations sections from version two were combined for continuity and to reduce repetition.
- The information on types of connection interfaces considered in the Charging Systems section in version two, was separated out as its own section because it applies to both the charging systems and the vehicle.
- A glossary was added to the back matter of the guideline.

SECTION REFERENCES

CSA Group. (2016). *Use of electricity in mines* (Standard No. M421-16[R2016]). CSA Group. https://www.csagroup.org/store/product/M421-16/

CSA Group. (2022). *Flameproof non-rail-bound diesel-powered machines for use in gassy underground coal mines* (Standard No. M424.1:22. CSA Group. https://www.csagroup.org/store/product/2700953/

International Electrotechnical Commission. (2016). *Safety of machinery—Electrical equipment of machines—Part 1: General requirements* (Standard No. IEC 60204-1:2016). https://webstore.iec.ch/publication/26037

International Electrotechnical Commission. (2018). *Safety of machinery—Electrical equipment of machines— Part 11: Requirements for equipment for voltages above 1 000 V AC or 1 500 V DC and not exceeding 36 kV* (Standard No. IEC 60204-11:2018). https://webstore.iec.ch/publication/31752

International Organization for Standardization. (2016). *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 1:General requirements* (Standard No. ISO 14990-1:2016). https://www.iso.org/standard/63299.html

2. GENERAL BACKGROUND

This section provides a brief overview of the advantages and disadvantages of mobile trackless BEVs in underground mining when compared to diesel vehicles. It is intended for those who are starting to think about whether the technology is right for their situation.

Most underground mining operations today make extensive use of diesel-powered trackless mobile vehicles. There are many vehicles that range from prime movers for transporting ore and waste to utility vehicles for installing and maintaining mine infrastructure. As battery technologies advance, many companies are seeing the benefits of replacing diesel-powered trackless vehicles with BEVs in underground mining operations.

2.1 ADVANTAGES OF BATTERY ELECTRIC VERSUS DIESEL VEHICLES

The advantages of employing BEVs can be great, especially for underground mining. However, the extent of the benefits will depend on the specifics of the mine.

BEVs can enable a safer, cleaner, and healthier working environment by reducing products of combustion and liquid pollutants (e.g., oil, transmission, and radiator fluid) from the working environment and reducing noise exposure levels. The noise, heat, and odour generated from diesel engines can negatively affect the underground work environment. Further, diesel emissions include carbon monoxide (CO) and dioxide (CO_2), nitrogen (NO_x) and sulphur oxides (SO_x), hydrocarbons, and diesel particulate matter (DPM). These emissions 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). For a specific example on how BEVs improve working conditions by reducing diesel exhaust-related contaminants, see the results of a field study at a Finnish mine as described in Halim et al. (2021).

- Regenerative Braking and Ramp Design (Mine Design), Section 4.2.2
- Ventilation and Cooling (Mine Design), Section 4.7
- Braking (BEV design), Section 5.2
- Performance Standards, Section 9

Another key advantage is that BEVs offer an alternative to prohibitive ventilation costs associated with diesel equipment during underground mine expansion and production programs. Mine regulations throughout the world have evolved to mandate appropriate ventilation measures to clear emissions. For example, 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 personnel underground from diesel emissions requires expensive and electricity-consuming ventilation and cooling infrastructure. As mines descend to greater depths, the demands for further ventilation grow. This limits the economic viability of deep greenfield mines as well as the expansion of existing mines to greater depths.

In many cases, by eliminating the main source of air pollution in underground mines using BEVs, airflow requirements can be significantly reduced. In deep mines where cooling is a requirement, airflow reduction translates into a corresponding decrease in cooling requirements. In addition, by eliminating diesel exhaust requirements, a one-pass-then-exhaust ventilation strategy is no longer necessary, thereby allowing partial recirculation/reuse of air leading to a further reduction of airflow to and from the surface.

In addition to decreased air volumes, BEVs can also reduce refrigeration costs through decreased heat loading and friction braking. BEVs are also able to implement regenerative braking and do not idle at rest.

BEVs can also provide some performance advantages such as low speed torque characteristics that can enhance vehicle acceleration, responsiveness, and traction control through use of electric traction motors. These advantages can lead to higher vehicle productivity. They also often have fewer moving parts, which can potentially require less maintenance and generate less heat (this has been a finding for road vehicles, see Harto, 2020).

Environmental and social benefits are also a key consideration. BEVs can decrease the greenhouse gas (GHG) profile from both the elimination of direct diesel combustion and a net decrease in power consumption due to ventilation savings. BEVs also are broadly perceived as socially acceptable (Hanke, Hülsmann, & Fornahl, 2014).

2.2 DISADVANTAGES OF BATTERY ELECTRIC VERSUS DIESEL VEHICLES

BEVs also present new challenges for mines regarding infrastructure, maintenance, and operating requirements and constraints. Depending on the situation, they might not always be the appropriate choice for the mine operation to achieve their goals. The potential benefits listed above also might not apply to all situations.

Even with recent advances in battery technology, one of the key benefits of fossil fuels over electric is high energy density. 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). Therefore, when adopting BEVs, allowances need to be made in mine planning and scheduling to allow for charging. In addition, charging infrastructure will become a key requirement for a mine.

The higher energy density of diesel can be somewhat offset by lower efficiency of use. A large portion of the energy content is lost as heat during diesel combustion and through losses in transmissions, torque converters, and gearboxes. By comparison, the loss of energy to heat in BEVs is substantially lower, as noted above. Despite these compensations, the net energy content is still substantially higher in diesel than LIBs.

Standardized fuel is another key advantage of diesel equipment. Refineries handle the complexities of converting raw petroleum products into a portable fuel. BEVs do not share this convenience because the battery pack can be a more complex energy storage medium and the battery charging process can be more complicated. The BEV market is developing quickly with updated products increasingly being commercialized. As such, there are many options available for charging batteries, although these options are not yet standardized.

Another consideration is how the sites are powered. Depending on the net power demand, those implementing BEV equipment on remote sites where site electricity is generated by diesel-powered generators should evaluate if they add more load to a system that is generally designed without considering BEVs and if it could be balanced by ventilation savings.

- Charging Infrastructure, Section 4.6
- Charging Systems and Methods, Section 7
- Types of Charging and Connection Interfaces, Section 8

SECTION REFERENCES

American Conference of Governmental Industrial Hygienists. (2012). *Threshold limit values and biological exposure indices.* Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Hanke, C., Hülsmann, M., & Fornahl, D. (2014). Socio-economic aspects of electric vehicles: A literature review. In M. Hülsmann and D. Fornahl (Eds.), *Evolutionary paths towards the mobility patterns of the future, Lecture notes in mobility*. Berlin Heidelberg: Springer Verlag. https://doi.org/10.1007/978-3-642-37558-3_2

Harto, C. (2020). *Electric Vehicle Ownership Costs: Chapter 2- Maintenance. Consumer Reports*. https://advocacy.consumerreports.org/wp-content/uploads/2020/09/Maintenance-Cost-White-Paper-9.24.20-1.pdf

Halim, A., Lööw, J., Johansson, J., Gustafsson, J., van Wageningen, A., and Kocsis, K. (2021). Improvement of Working Conditions and Opinions of Mine Workers When Battery Electric Vehicles (BEVs) Are Used Instead of Diesel Machines – Results of Field Trial at the Kittilä Mine, Finland. *Mining, Metallurgy, and Exploration.* https://doi.org/10.1007/s42461-021-00506-8

International Agency for Research on Cancer. (2012, June). *IARC: Diesel engine exhaust carcinogenic* [Press Release No. 213]. World Health Organization. https://www.isglobal.org/en/-/iarc-diesel-engine-exhaust-carcinogenic?inheritRedirect=true

3. BUSINESS CASE

3.1 INTRODUCTION

This section includes guidance on developing the business case for BEVs and considering the scope for implementation. It expands on key considerations including revenue, capital cost, operating cost, health and safety, and environment and community. It is intended for those at the conceptual stage looking to understand and develop the business case for BEVs.

As noted in Section 2, all-electric mines can offer distinct advantages compared to conventional mines, especially in reducing diesel emissions and associated negative impacts on personnel health. However, compared to conventional mines, all-electric mines also present several challenges that should be considered. These challenges can affect the business case from revenue, capital cost, and operating cost perspectives.

Table 3.1 provides some guidance on considering the scope for implementation and reviewing these challenges and advantages. This table is intended to identify considerations for developing the business case for BEVs but is not intended to be exhaustive. The check marks are assigned to columns for existing underground operations, underground greenfield projects, and surface operations. These check marks are intended to indicate situations where these considerations are especially important, but the absence of a check mark does not mean that the consideration will not apply in that type of operation. Surface operations are also considered here for comparative purposes.

- Some reference cases with examples of data comparing BEVs to diesel vehicles can be found in Appendix A

Table 3.1. Business Case Guidance for Considering the Scope for Implementation

	Existing underground operations	Underground greenfield projects	Surface operations
Revenue			
Differences in productivity due to air quality	✓	✓	✓
Differences in productivity due to work environment temperature & humidity (particularly related to work/rest regimes in hot work environments)	✓	✓	
Differences in productivity compared to conventional diesel (e.g., due to availability, utilization); performance improvements of BEV equipment and battery charging/swapping requirements	✓	✓	✓
Potential to mine traditionally uneconomic orebodies	✓	✓	
Capital cost			
Cooling battery-related infrastructure such as charging areas	✓	✓	✓
Infrastructure for storing and charging batteries	✓	✓	✓
Diesel fuel handling system	✓	✓	✓
Capital expenditures for BEVs and associated batteries vs diesel equivalent	✓	✓	✓
Differences in ventilation-related capital	✓	✓	
Electrical infrastructure costs on-site to distribute power to operations, including possible upgrades to accommodate additional loads for chargers	✓	✓	✓
Electrical infrastructure costs to get power on-site through utility or self-generation	✓	✓	

Table 3.1. Business Case Guidance for Considering the Scope for Implementation (continued)

	Existing underground operations	Underground greenfield projects	Surface operations
Differences in mine air heating and/or cooling-related capital	✓	✓	
All other mine design related changes affected by the introduction of BEVs, such as quantity, and size of drifts and shafts	✓	✓	
Potential for government subsidies or grants for using green technologies	✓	✓	✓
Operating cost			
Differences in overall mine energy requirements and energy costs	✓	✓	✓
Differences in ventilation-related operating costs	✓	✓	
Diesel fuel transportation and storage systems and the related logistics costs	✓		
Mobile equipment maintenance, labour costs, and parts warehousing costs	✓	✓	
Choices in charging/fuelling strategies can drive operating costs (e.g., fuel truck operations and swap vs fast charge)	✓	✓	✓
Differences in carbon taxation or fuel surcharges	✓	✓	✓
Battery handling costs including storage, disposal, and recycling	✓	✓	✓
Health, safety, environment, and community			
Workplace conditions; vibrations, noise, air quality, temperature, humidity	✓	✓	✓
Environmental emissions; air & noise emissions, mine water effluent quality		✓	✓
Environmental risks; hydrocarbon spills on-site, supply chain spill risks	✓	✓	✓
Local community; social acceptance of BEV vs diesel		✓	✓
Investors, regulators, general public perception, broader social license, and brand value	✓	✓	✓
"Responsibility beyond compliance"—exceeding the minimum regulatory requirements	✓	✓	✓
Risk of regulatory reductions in NO_x and DPM	✓	✓	
Training	✓	✓	✓
Workplace cultural conditions and change management	✓	✓	✓
Meeting GHG-specific sustainability commitments	✓	✓	✓

3.2 REVENUE

In the context of this guideline, revenue refers to the ways in which productivity and performance affects the volume mined—and thereby affecting the revenue of the mine—rather than financial calculations.

- Performance Standards, Section 9

3.2.1 Performance and Productivity

BEVs can enable performance improvements that increase tonnes mined, thereby increasing revenues. For example, with diesel equipment, available ventilation volumes can affect the engine size and limit some aspects of the vehicle's performance or the equipment fleet size that can be deployed. These constraints do not exist for BEVs. Thus, more powerful electric drives can be selected for units with similar payload capacity, potentially resulting in improved equipment performance (e.g., breakout/lifting capacity,

acceleration, and speed). Lifting these constraints through use of BEVs would be beneficial if the mine is the bottleneck in the production chain. Otherwise, this higher productivity would be left unused by the mill.

However, these performance improvements can be somewhat offset by the time required to charge or swap batteries. It is recommended to study these impacts on overall productivity to confirm that BEV adoption meets the expectations of the mine.

It is also recommended to monitor vehicle performance not only from a preventive maintenance standpoint but also to obtain feedback on operator performance. This monitoring can accelerate adaptation to battery-powered vehicles and improve overall vehicle performance.

If BEVs are being used as a trial to confirm the business case, data collection (e.g., from ventilation and equipment performance) along with analysis of the diesel and BEV options need to be considered prior to the equipment arrival. Once equipment has arrived, it is also beneficial to accumulate early performance data to verify operating performance and be used if there is a simulation phase before confirming the operationalization of the BEV implementation.

3.2.2 Traditionally Uneconomic Orebodies

Upgrading or building ventilation infrastructure to accommodate diesel equipment can be technically challenging and/or cost prohibitive. Therefore, the fewer ventilation constraints associated with low-emission BEVs can be a factor in making the development of some traditionally uneconomic orebodies profitable.

3.3 CAPITAL COSTS CONSIDERATIONS

3.3.1 Overall Infrastructure Considerations

When considering a change to BEVs, the infrastructure factors to consider depend partly on whether the operation is a modification of an existing brownfield operation or a new greenfield operation. Existing mine infrastructure has the potential to limit the benefits because it was designed for a different context. Considering the capital costs and potential savings associated with mine infrastructure is a key part of the business case. For greenfield operations, the overall mine system (e.g., layout, operating approach) can be optimized with a mixed fleet of BEVs, diesel hybrid vehicles, diesel vehicles, tethered equipment, and trolley-assist systems, or a complete non-diesel operation.

3.3.2 Vehicle and Battery Assets

When comparing BEVs with diesel equivalents, the capital expenditure depends on the method of paying for the battery. Battery costs can be significant and can either be an upfront capital expenditure or as part of an operational expenditure approach through rental or lease.

As the adoption of BEVs increases, battery and electric components are expected to further improve while costs are expected to decline, enabling OEMs to continue to improve vehicle design for both performance and cost.

Battery disposal is an issue that needs to be addressed because batteries can be used for new applications before they need to be recycled.

- Charging Philosophy, Section 4.6.2
- End-of-Life (Energy Storage Systems), Section 6.3.9

3.3.3 Ventilation and Cooling Infrastructure

In terms of capital expenditure, using BEVs generally results in a decrease in required air volumes, which in turn requires smaller and potentially fewer ventilation shafts, smaller access drifts, and smaller fans. These benefits can reduce costs for all-electric greenfield mines, but they can be limited for brownfield or mixed fleet mines. Possible questions to be considered include:

- Can ventilation and cooling infrastructure be reduced?
- What changes are possible with the ventilation plan?

- Ventilation and Cooling, Section 4.7
- Developing the Ventilation Design and Plan, Section 4.7.7

- Is ventilation and cooling driven by dilution or are there other drivers such as radon and dust?
- Will future infrastructure expansions be reduced or eliminated?

3.3.4 Electrical Infrastructure and Power Distribution

Possible questions to consider when planning or designing electrical infrastructure and distribution of power include:

- Is there sufficient electrical energy available at all times of the mining cycle?
- What is the impact of different daily demand load variations?
- How will BEVs affect the underground distribution system and the potential for power infrastructure upgrades?
- Do charging requirements and the infrastructure to facilitate them impact the supply to the mine?
- Are there potential fleet size increases that will change the charging demand and pose additional constraints on economics?
- Is it possible to have early standardization on charging infrastructure across OEMs?

- Charging Philosophy, Section 4.6.2
- HVDC Electrical System, Section 5.3
- Charging Systems and Methods, Section 7

While the capital cost implications for BEV-specific infrastructure are significant, choices based on the charging philosophy can have a positive impact on the total cost of the ownership calculations. In addition to any changes with the upstream electrical distribution system, a complete system of chargers needs to be implemented. The mine could have one charger associated with each piece of equipment, or one charger for multiple pieces of equipment. The charging infrastructure affects the mine's internal environment. For example, these chargers become localized heat sources that require additional ventilation.

For new projects, total mine power requirements should be taken into consideration for self-generation or utility connection decisions. As the net power demand for most projects drops due to ventilation savings, it could result in significant capital savings.

3.3.5 Layout

Possible questions to be considered when planning the layout include:

- Is equipment operating on an existing layout or future levels that can be designed around BEVs?
- Will the primary ventilation network change to accommodate the location of the charging stations?
- Are there changes in the mine layout such as charge station cut outs, parking location of vehicles, roadway grades and directions, and maintenance shop layout/requirements?
- Can a reduced vent ducting size translate into smaller drift sizes?

- Personnel Movement and Parking, Section 4.4
- Mine Layout and Infrastructure, Section 4.2

3.4 OPERATING COST CONSIDERATIONS

While there can be many upfront costs with implementing BEVs, operational expenditures can be improved with their use.

3.4.1 Overall Energy Requirements and Costs

One of the key differences between mobile diesel equipment and BEVs is the amount of energy used to perform the same work. Additional considerations include:

- Benchmark operational costs from diesel mines do not apply to electric mines
- The power required for ventilation is typically lower for BEVs

OEMs should be able to provide the energy requirements for required duty cycles to inform the energy budget for electric mines.

Utilizing BEVs could represent a significant change in the power distribution strategy for both greenfield and brownfield mines. For example, 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 needs to be reviewed and trend monitored to determine how it might affect any existing infrastructure and protection equipment.

Effects from any additional electrical equipment, such as variable frequency drives, should be evaluated to confirm that power quality is maintained. Possible questions to be considered include:

- What is the net change of electrical power for the mine based on the total?
- How do the requirements vary during the day?
- What can be done to rebalance the load?
- How is power quality affected by the type of loads?
- What provisions will need to be made?

Charging infrastructure decisions affecting workflow and equipment availability should also be considered.

- HVDC Electrical System (BEV Design), Section 5.2
- Incoming Power System (Charging Systems), Section 7.4
- Performance Standards, Section 9

3.4.2 Differences in Ventilation-Related Operating Costs

The following are some key considerations around differences in ventilation-related operating costs associated with BEVs:

- Operational savings can also be substantial in electricity costs given the affinity curves of ventilation fans.
- Depending on the local climate, a lower air flow rate can yield savings in winter heating and/or refrigeration costs. Conversely, energy consumed in winter months to heat the ventilation could be increased for non-thermal engine mines.
- Smaller fans generate less heat, further contributing to heat savings of BEV compared to diesel mobile equipment.
- Ventilation on demand systems complement the energy savings already associated with BEVs while allowing for efficient blast gas clearing times. See Gyamfi, et al. (2021) for a case study that found that combining BEVs with ventilation on demand saves ventilation power costs but that the presence of strata gases (e.g., radon) restricts their reduction.

- Ventilation and Cooling, Section 4.7

3.4.3 Maintenance Costs

Maintenance costs can be lower 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 many interconnected sensors to monitor and warn the operator of faults and provide trending data for the predictive maintenance system.

Using BEVs presents an opportunity to reduce maintenance time, effort, and expenses already attributed to traditional vehicles. In addition, maintenance cost savings can be targeted with the reduction in mine ventilation, refrigeration requirements, and other support systems which accompany BEVs. It is recommended that maintenance shop requirements consider space requirements for chargers and clearances for working on high-voltage systems.

- Maintenance Areas, Section 4.3
- Charging System Operation and Maintenance, Section 4.6.6
- Drivetrain, Section 5.6
- Maintenance and Service Areas on the Equipment, Section 5.9

The design of the BEV drivetrain will determine the extent of operation maintenance savings. Vehicles that replace the diesel engine with an electric one and still require the full mechanical drivetrain will inherently have more moving components than fully electric drivetrains and are therefore likely to have higher maintenance costs. Batteries also require maintenance that needs to be considered when defining maintenance costs, equipment availability, and charging strategy.

While the benefits above can reduce planned maintenance time and cost, BEVs have the potential to increase operator-related, non-planned events (e.g., charging cable damage, receptacle, or plug damage). Further, while fixed maintenance costs can be reduced for fuel stations, they can be increased for charging stations and cranes. Differences in labour costs are also a consideration.

3.5 HEALTH, SAFETY, ENVIRONMENT, AND COMMUNITY

3.5.1 Working Environment

The general improvement in the working environment—including benefits such as no emissions, less noise, and reduced heat and vibration from electric drives—is another potential benefit of BEVs.

BEVs present an opportunity to reduce heat, particularly in warm climates and in deep mines, which can lower the need to implement work/rest regimes depending on the ventilation and cooling plan implemented in the mine. Choice of energy source might also affect external mine related emissions, which can contribute to support from the communities in surrounding areas.

While BEVs offer many health, safety, environmental, and social (community) advantages, they can also present change management considerations around mine rescue and new risks such as battery fires and electrical shocks.

• Risk Assessment, Section 4.10

3.5.2 Training

Different skills are required to troubleshoot and replace components. It is important to consider the costs associated with training personnel who currently work with diesel equipment to operate and maintain BEVs.

3.5.3 Sustainability and Community Acceptance

The use of BEVs can help operations meet GHG and work environment-related sustainability goals and commitments and potentially improve their license to operate credentials and access to certain projects.

SECTION REFERENCES

Gyamfi, S., Halim, A., and Martikainen, A. (2021). Development of Strategies to Reduce Ventilation and Heating Costs in a Swedish Sublevel Caving Mine – a Unique Case of LKAB's Konsuln Mine. Mining, Metallurgy & Exploration. https://doi.org/10.1007/s42461-021-00483-y

4. MINE DESIGN AND OPERATIONS

4.1 INTRODUCTION

Mine design and operations should be adjusted to accommodate charging methods, mine cycle and schedules, risks, and maintenance and operations requirements associated with BEVs. The potential to lower ventilation requirements is a primary driver for making mine design changes to accommodate mine electrification, whether the application is for a greenfield or brownfield site. However, when designing a layout for an all-electric (battery and/or tethered) or hybrid mine (mixture of diesel vehicles and BEVs), additional infrastructure or adaptations to existing infrastructure might be required throughout the mine to maintain and operate the BEV fleet.

This section provides guidance and considerations around mine design and operations to accommodate BEVs, covering the following:

General note on safety content in this section

Safety is considered throughout this section (see the navigation below). Safety considerations that might affect mine design include:

- Noise
- Power and voltage
- Hazards specific to ventilation design
- Air quality (DPM, dust, moisture, and radon, if present)
- Heat
- Fire
- Geotechnical aspects

High-level risk assessments and safety training are also considered.

Mine Layout and Infrastructure (Section 4.2) Provides a brief discussion around some of the major aspects to consider when tailoring a mine for BEVs, including content on ore/waste handling systems (OWHS) and on regenerative braking as a method of mitigating the potential limitations associated with the energy density of batteries.

⚠ Discussion of high temperature conditions associated with regenerative braking (Section 4.2.2).

Maintenance Areas (Section 4.3) Outlines some considerations around how maintenance areas should be equipped and designed to accommodate BEVs.

⚠ Enabling the safe handling of batteries and electrical components is a key focus of this section.

Personnel Movement and Parking (Section 4.4) Outlines the considerations for personnel movement and parking compared to a conventional diesel mine, including guidance on shaft and ramp access.

⚠ The potential need for safeguards associated with chargers in parking locations is noted (Section 4.1.1).

Mobile Electric Equipment (Section 4.5) Identifies commonly used types of mobile electric equipment and key mine design considerations associated with them.

⚠ No specific safety guidance.

Charging Infrastructure (Section 4.6) Outlines some key considerations required in designing the charging infrastructure to confirm availability of fully charged batteries.

⚠ While it is not directly focused on safety, designing the charging infrastructure for safety underpins much of the guidance in this section, particularly around the charging station layout.

Ventilation and Cooling (Section 4.7) Provides insight on design criteria of ventilation and cooling in electric mines in contrast to traditional diesel mines.

⚠ Safety aspects of ventilation and cooling are considered throughout this subsection, including heat, dust, gases, air quality and temperature, high risk zones, and monitoring systems.

Battery and Fire Safety (Section 4.8) Describes battery fire risk and emergency response from a design and operations perspective.

⚠ Core safety section.

Training (Section 4.9) Outlines some key considerations around training that all personnel working with or around a BEV need in order to understand the operational differences, make sure safe practices are used, and identify and avoid potential hazards.

⚠ Identifies some safety training and procedural needs associated with BEVs such as daily inspections and understanding performance differences.

Risk Assessment (Section 4.10) Provides guidance to help the end user understand what to consider when developing a risk management framework for the adoption of BEVs in mining including financial, production, health and safety, and environmental risk considerations.

⚠ A table on health and safety risks (Table 4.10) summarizes a range of risk sources and possible treatments for fire/explosion risk, asphyxiation, electric shock, arcing fault, equipment runaway, and lack of noise.

4.2 MINE LAYOUT AND INFRASTRUCTURE

BEVs have several limitations relative to traditional diesel equipment that affect mine design and planning; the most important being their limited range and the time needed to charge. The key to a successful BEV-based mining development will be confirming the mine is planned and equipped to accommodate the BEVs while also fully harnessing the benefits that come with them. The following sections provide a brief discussion around some of the major aspects to be considered when tailoring a mine for BEVs.

- Performance Standards, Section 9 (describes performance information to consider for planning)

4.2.1 Ore/Waste Handling System

The ore/waste handling system (OWHS) is the most likely to be affected by the implementation of an electric fleet 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. This subsection focuses on the impact of electrification and not on OWHS design or current methods (e.g., diesel equipment, conveyors, or train cars).

New optimization methods are likely to follow broader adoptions of BEVs. For example, if it is possible to haul ore downhill, regenerative braking can optimize the use of gravity to capture some of the kinetic energy depending on several factors including the OEM, grade, and site conditions. This process would typically run as follows:

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/waste (discharged to X% – losses)
3. BEV travels down-ramp to a destination prior to entering the loading pocket (based on the elevation in the mine, the BMS determines the ratio of regenerative and actual braking to use to charge 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, alternative 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 weight and distance. However, this approach might not be feasible in some top-down mining operations due to factors such as orebody geometry and location of processing plants, therefore a cost-benefit analysis should be undertaken to determine if it is possible.

4.2.1.1 Trolley Assist Systems

In underground settings, trolley assist systems for OWHS are typically used for uphill haulage using overhead conductors that are designed for use by electric motors. With the move towards electrification of the mining fleet, the charging opportunity in ramps or drifts using an overhead power bar system is becoming more attractive.

- Alternative Charging Systems and Equipment Types, Section 7.5.6

Some challenges associated with mine design and trolley assist systems include:

- Requirements for fixed infrastructure and level surfaces

- The need for well-constructed and maintained roads, which can be challenging with frequent moves to new production areas/zones
- High infrastructure cost for the trolley line and operational road maintenance (e.g., mine planning having to allow for downtime associated with electrical lines and supports being extended and relocated)

Including a trolley assist system in an underground mine can introduce challenges with the interaction between electrical cables and mine personnel. In most mines, permanent services are installed in main haulage-ways, but service personnel sometimes need to access these services for repairs and/or extension, thereby creating a potential for this interaction.

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.

BEVs with trolley assist capabilities where trolleys are installed over permanent thoroughfares in the mine are an emerging technology that could provide the following additional operational advantages:

- Opportunistic charging when in contact with the trolleys over selected sections of the mine with permanent roadways, delaying or eliminating battery swap during a normal shift
- Allowing easier maintenance retrieval from the working areas to the workshop
- The combination of battery and trolley assist could minimize mine planning inflexibility associated with fixed infrastructure

See Paraszczak et al. (2014) and Willick (2010) for further information on the benefits of trolley assist systems in underground mines. CSA M421-16 also provides information on trolley assist systems and infrastructure.

4.2.2 Regenerative Braking and Ramp Design

- Braking System (BEV Design), Section 5.2
- Regenerative Braking Systems (Performance Standards), Section 9.3.3

Diesel equipment can either use the engine or friction braking on downgrade tramming to manage speed. The net result is that both generate heat that is emitted to the environment. Most modern BEV motors convert most of the kinetic energy into electric energy that goes back into the high-voltage batteries. This process is known as regeneration. The amount of regeneration that can be achieved depends on ramp grade, gross vehicle weight, speed, ramp conditions, and operator behaviour. Regeneration has the following advantages for BEVs:

- Longer BEV range
- Lower energy consumption (higher efficiency)
- Batteries can be sized smaller
- Less heat is introduced into the mine environment
- Maintenance savings on brakes

The mine layout should maximize the benefits of regeneration. In OWHS planning, this feature can be particularly beneficial due to high gross vehicle weights. A BEV hauling loads up-ramp and returning empty down-ramp has a significantly different energy requirement than one hauling loads down-ramp and returning empty up-ramp, which drives the requirements for battery capacity and charging/swapping frequency.

A BEV travelling down-ramp with a full battery relies on other means to dissipate the energy, such as turning electrical energy back into heat through braking resistors or using the service brakes. The following strategies can be considered to avoid tramming down-ramp with a full battery:

- Select charging locations and the designed state of charge (SOC) at the end of the charge cycle: In general, chargers are more effective at lower elevation because they can top up batteries.
- Limit the charge into the battery when equipment needs to tram down-ramp from the charging location: Limiting the charge will result in the battery having sufficient capacity to absorb regeneration.

Braking resistors should be monitored to indicate when there are high temperature conditions and/or provide controls to avoid excessive temperature and to enable continuity and optimal resistance value. An alert should be sent when those values are outside of normal ranges.

4.3 MAINTENANCE AREAS

Although BEVs typically have fewer wear components compared to diesel vehicles, they still have many components that require traditional service. For example, hydraulic systems, mechanical brakes, moving joints, bushings, bucket lips, fire suppression systems, tires, and greasing systems will require regular maintenance. BEVs still require properly equipped maintenance areas to service the equipment. Typical designs optimizing shop workflow with repair bays and specialty bays for welding, tire handling, or lube are still required.

- Charging System Operation and Maintenance, (Section 4.6.6)
- Maintenance and Service Areas on the Equipment, (Section 5.9)

Mines designed for BEVs should consider the following for the maintenance areas:

- A crane or lift with larger capacity if needed for lifting/handling larger batteries, and these might also require higher shop heights to enable sufficient clearance
- Additional rigging requirements for handling batteries if needed
- Charging availability at the shop exit to allow equipment to be charged and ready for use at the completion of maintenance
- Test load (with DC/DC controller) to test or safely discharge a battery
- Battery fire containment and/or fire control within the shop space, and a containment area to store damaged batteries
- Electric motor repair space with specialty tools for testing motors
- Low-capacity portable chargers that can move within the maintenance area to recover discharged batteries or boost the charge level; these chargers will need to be appropriate for the battery
- Battery storage space to store spare batteries
- Battery maintenance space if batteries are to be maintained on-site

4.4 PERSONNEL MOVEMENT AND PARKING

This section outlines the considerations for personnel movement and parking compared to a conventional diesel mine.

4.4.1 Shaft Access

In a shaft accessible mine, BEVs have specific charging and parking requirements that should be considered in the design.

When charging is done at the end of the shift, movement between the shaft station and BEVs needs to be considered. Some equipment such as jumbos would not typically report to the shaft station, instead remaining closer to active headings as they do in diesel mines. Two key personnel transport methods are:

- Walking
  - BEVs are parked close enough to shaft stations for personnel to walk to/from them
  - Sufficient parking locations and chargers, and sufficient power supply chargers are required for all BEVs
  - Longer charger cables might be required in parking areas around shaft stations to distance and safeguard the chargers from traffic and dust
- Personnel carriers
  - Located near the shaft station to transport personnel to locations in the mine
  - Can bring personnel to parking locations
  - Can bring personnel to mining levels to reach mining equipment
  - Consider charging personnel carriers near work areas once all personnel are delivered
  - Rail systems

4.4.2 Ramp Access

Group travelling is strongly encouraged in a ramp-accessible mine because long uphill travel at end-of-shift could deplete BEV batteries. It can be cost-effective to transport personnel in and out of the mine in dedicated group transportation BEVs; these are charged during shift to be ready for shift change.

4.5 MOBILE ELECTRIC EQUIPMENT

Different types of mobile electric equipment such as tethered equipment, trucks, load-haul-dump (LHD) machines, and auxiliary vehicles have different charging configurations and will require different design and operations considerations. Figure 4.1 summarizes some of the considerations based on these differences. Alternate haulage methods such as conveyors, electric-powered trains, trolleys and monorails, railed conveyor, and continuous haulage systems will also have specific requirements.

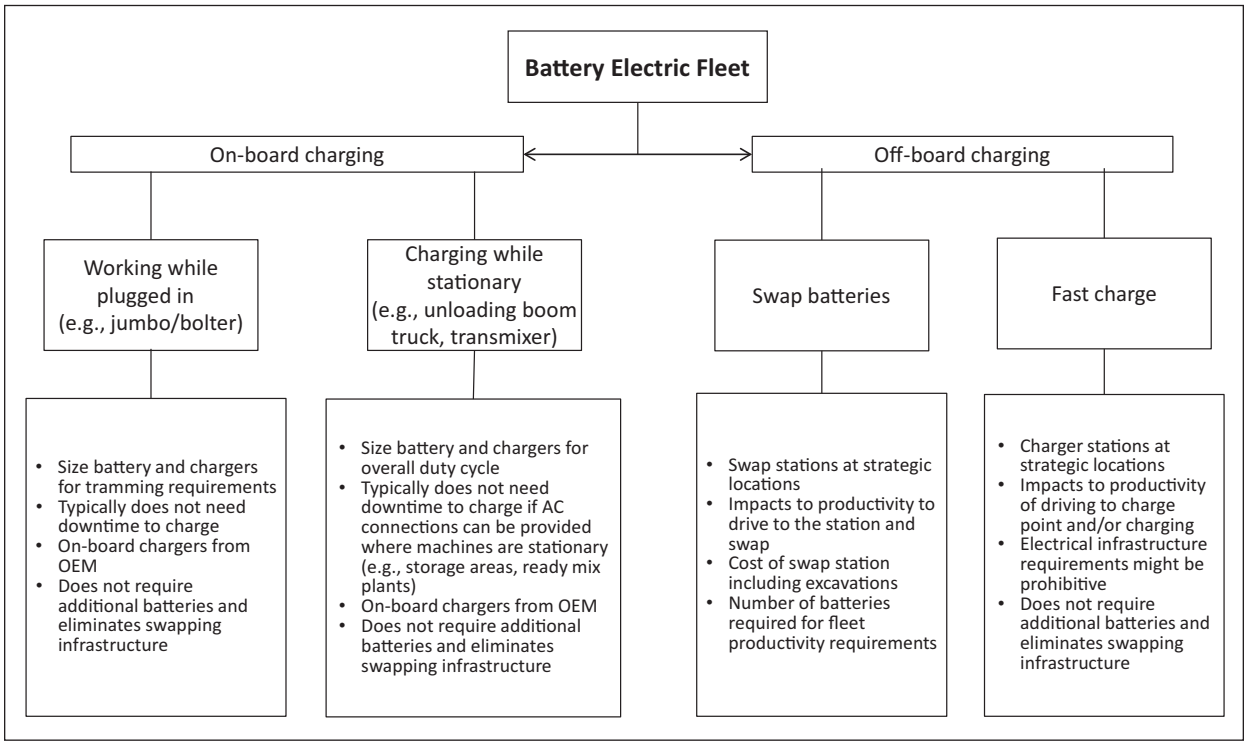


Figure 4.1. Electric Fleet Design Considerations (non-exhaustive)

4.5.1 Charge-While-Operating Equipment Group (Tethered)

Charge-while-operating equipment is typically plugged into alternating current (AC) power while performing work and travel under battery power when moving between work locations. This group typically includes:

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

- On-Board Charging, Section 7.5.1
- Alternative Charging Systems and Equipment Types, Section 7.5.6
- On-Board Charging from Alternating Current (AC) Supply Interface, Section 8.2
- Duty Cycle, Section 9.2.1

Because charge-while-operating (tethered) equipment operates under AC power most of the time, it only requires a smaller capacity battery for travel periods. 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.

The duty cycle of the battery on each piece of equipment should be reviewed to calculate the charge frequency, which can then be used to determine the number of chargers required on each mining level. Off-board charging can be an

expensive option for charge-while-operating equipment, and it can also increase the complexity and decrease the efficiency of the mining cycle.

Some operational challenges associated with these systems include:

- Mine planning to cater to cable length (restricted to approximately 250 m because longer lengths can make the cable drum too large and heat generation within the wound cable too great).
- The anchor for the cable to electrical supply interface point has to be robust to prevent anchors from pulling out of walls or plinths. Any water/corrosion caused on the anchor lines/bolds could cause them to detach. Some of these challenges can be mitigated with playout cables.
- The associated electrical cable tension spring at anchor points typically requires regular replacement depending on cable cycles per year.
- The outlayed cable could vibrate at any moment, requiring all access to the area to be cordoned off (physical barriers) to eliminate possible incidents involving personnel/equipment.
- Scheduled maintenance at work stations requires disruption to the working area (stopped while being retrieved) and between working area and workshop (portable generator set hooked up to relocate vehicle).
- LHDs can also be tethered, which can cause logistics constraints for other equipment operating in the vicinity because they are not constrained to one work area and are tramming back and forth.

4.5.2 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

4.5.3 LHD Machines

Mine design and operations 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
- Tethered with battery assist options

4.5.4 Auxiliary Vehicles

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

4.6 CHARGING INFRASTRUCTURE

Once personnel transport needs are determined, the equipment is chosen, and the mine is generally laid out, then the charging infrastructure can be defined. This subsection focuses on general considerations for the overall infrastructure, layout, and planning required to accommodate charging. The charging philosophy and factors depicted in Figure 4.1 will influence the mine layout and should be considered in the early stages by all participants of the mine design team.

Overall considerations relating to the charging method include:

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

- Charging Systems and Methods, Section 7
- Types of Charging Methods, Section 7.5
- Types of Charging and Connection Interfaces, Section 8

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

- Charging stations at dedicated locations
- Shared chargers
- One size fits all
- Centralized charging options where there is a power station with a number of charging posts connected to it so that one power cabinet would be charging more than one system at a time
- Specific chargers match specific equipment
- Footprint of the power source for the charger itself and room to park a BEV to leave it aside to charge

4.6.1 Design Prerequisites

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

- Selected charging philosophy
- Expected run-time for the equipment—with input from OEMs—based on size and required duty per shift (accounting for personnel travel time, breaks, setup, and other battery downtime)
- Equipment duty cycle, including opportunity charging
- Number of charging stations, chargers, batteries, and types of chargers required throughout the mine and their locations based on the equipment fleet and charging philosophy

4.6.2 Charging Philosophy

Without careful design, there is a risk of ending up with incompatible charging stations throughout the mine. The ultimate objective is to make charging 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, determined through modeling that incorporates BEV charging philosophy options. Since electrical infrastructure is spread throughout the mine, chargers can be added as needed. When laying out the main power cables throughout the mine, junction boxes can be included in advance if the potential need for future charging stations is recognized. Junction boxes add some upfront costs but can create an opportunity to add additional charging stations in the future.

4.6.2.1 Establishing the Charging Philosophy

The choice of charging arrangement from among the four approaches described in Section 7.5 (on-board charging, off-board charging of on-board batteries, off-board charging of off-board batteries, and hybrid charging) should be tailored to a given mine based on many factors, including the following:

- The energy consumption model to determine the operational plan and charging philosophy
- Whether the mine will be fully electric, or if some diesel vehicles will be employed
- If the mine is a new greenfield development or existing brownfield mine
- The size and capacity of vehicles and/or mine workings
- Available battery capacity for a given vehicle class
- Haulage routing uphill, downhill, or at grade
- Available and desired ventilation
- Shift schedule relative to when charging will take place

The type of implementation can also affect many of the factors above. For example, if a large battery would prohibit uphill haulage, an existing mine with ramp access to greater depths might be forced to employ some diesel haulage vehicles or combine the battery usage with trolley systems. By contrast, a greenfield mine could choose to sink a deeper shaft to enable downhill haulage to take advantage of BEV regenerative braking if it can be justified when considering the trade-off between increased capital costs for potential reduction in operating costs. Some key charging philosophy considerations include:

Consider standardizing the entire mine with one type of charger—to a certain extent, considering that chargers will be designed according to specific needs.

- If only small BEVs will be deployed and/or if charge time is not a significant concern, considering on-board charging could be appropriate.
- If multiple OEMs will be supplying BEVs, a standard charging protocol such as combined charging system (CCS) Type 1/Combo 1 (North America) or Type 2/Combo 2 (European) could be appropriate. In this case, the mine might consider developing internal procurement specifications that nominate the compatibility requirements for their infrastructure inclusive of the charge port connection.
- In the case of high use equipment such as LHD machines, those implementing them should investigate the advantages and disadvantages of dedicated vs. standard (e.g., CCS Type 1/Combo 1 or CCS Type 2/Combo 2) high-power chargers to implement on their operations.
- If using an automatic charging system and autonomous or semi-autonomous operation, a standard protocol such as CCS Type 1/Combo 1 or Type 2/Combo 2 is recommended for maintaining standardization across the assets.

- Off-Board Charging Interface, Section 8.3.1 (covers CCS, automated connection interfaces, and standardization in more detail)

Consider hybrid charging 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.

Carefully plan the parking arrangement for stationary charging stations with a designated parking spot for each BEV.

- For opportunity charging, allow space for bigger BEV equipment of the fleet.

For substantial deployment of BEVs of all sizes, consider equipping the mine with two capacities of standardized off-board chargers with universal charging interfaces.

- For large BEVs (LHD machines and haulage trucks), it is typically recommended to install high-capacity chargers. The mining company deploying BEVs should understand the different charging technologies and their benefits, but the OEM should specify the type of technology and specifications suitable for their equipment and perform any required analysis.
- 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.

If long uphill haulage is required, a battery swapping arrangement, additional charging stations on a long grade, opportunity charging stations, or a storage battery should be considered.

- This requires some infrastructure for battery removal, and likely involves cooperation with the OEM.

Chargers should have a wide output voltage range at different nominal voltages.

Consider charging locations to maximize the use of the battery operating range (e.g., hauling uphill, charger not at the top of the ramp to use regeneration downhill).

The battery run-time is affected by many variables. The following points should also be considered:

- If the battery run-time is longer than the shift length at the design duty, then shift-change charging could be simpler to implement. However, considering the human interactions and applying methods such as monitoring systems, post-shift checks, or other operating procedures to make sure the vehicle is ready for the next shift is recommended.
- If the battery run-time is marginally shorter or longer than the shift length at the design duty, then shift-change charging with opportunity charging, battery swapping, or possibly in-shift charging options could be implemented.

- If the battery run-time is substantially shorter than the shift length, then alternate methods such as battery swapping, in-shift charging, or opportunity charging would likely be a necessity.
- If using tele-remote or autonomous technology, then consideration should be given to operating equipment between shifts and during breaks.
- The definition of state of charge operating points can add constraints to the run-time. How run-time will be affected by battery capacity being diminished over time as it encounters more charge cycles is also an important consideration.

There could also be trade-offs concerning the physical size of the battery, the cost of the battery, and infrastructure requirements and costs for different battery capacities (e.g., additional reserve capacity can affect lifecycle costs and infrastructure costs).

As technology advances, other methods of charging such as trolley assist, inductive, or other advancing technologies could become more prevalent.

4.6.3 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 to reduce delays associated with charging.

4.6.4 Opportunity Charging

Opportunity charging refers to the situation where a BEV is stationary for a portion of time as part of its intended duty, and the BEV gets charged during that time. The result is that charging can occur without incurring additional downtime when compared to a diesel equivalent. Examples of such opportunity charging scenarios include:

- A boom truck that charges while loading and unloading supplies
- A transmixer that charges the battery while discharging the drum into a shotcrete sprayer
- A haul truck using fast charging within a cycle time from loading point to loading point, including a fast charge sequence
- A supervisor choosing to plug in a light vehicle to charge while talking to employees

For many ancillary vehicles, opportunities can be found during the shift to make use of this stationary time if there is a charger located where the vehicle is stopped. Locating the chargers on-board the vehicle usually reduces the amount of charging infrastructure that is required; a power supply such as a jumbo cable is typically all that is required as long as it complies with the company's internal standards.

4.6.5 Charging Station Layout

Considerations associated with the physical environment, the preparation of the charging area for installation, spacing and parking, battery swapping, power distribution, and fast charging are described in the following subsections.

- Safety Considerations (Charging Systems), Section 7.2
- Charger Installation, Section 7.3

4.6.5.1 Physical Environment

Chargers contain sensitive electronics that should be treated with care to survive for sustained amounts of time in harsh mining environments, which contain:

- Dust
- Humidity
- High salinity
- Sulphur fumes (which affect conformal coating)
- Heat
- Vibration
- Percussion blast
- Falling objects
- Water via failed pipes, dripping from the back, or partial flooding in the area
- Blasting gases or off-gases

Some of the key physical environment considerations are illustrated in Figure 4.2.

Because the charging station is an area where there will be fire risks associated with batteries and electricity, early detection systems are a key consideration so that events can be addressed as quickly as possible to make sure those operating the systems can take the appropriate measures. The level of detection will depend on several factors, including company insurance policies, company standards, regional regulations, and the type of mine and mining method. Any additional fire suppression requirements associated with the charging system and station should also be considered with reference to existing standards and regulations.

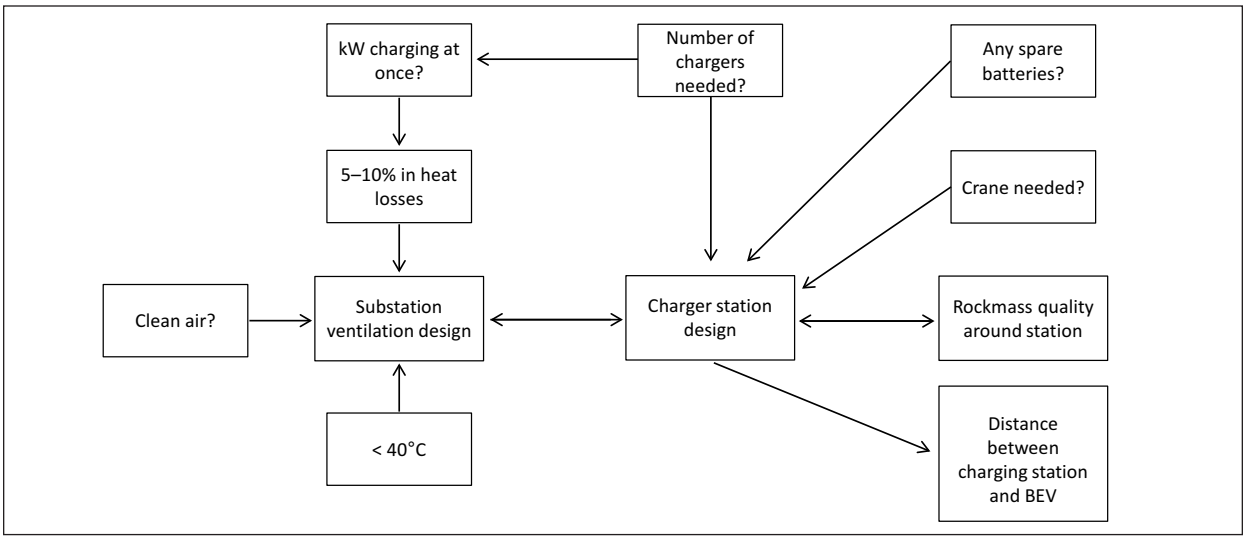


Figure 4.2. Air Volume Sizing Process for Battery-Powered Mobile Equipment

4.6.5.2 Preparing the Charging Area for Installation

Key features should be considered for the charging area before installation. Some of these are described in Table 4.1.

4.6.5.3 Spacing And Parking

Equipment spacing should follow OEM recommendations and local regulations, with charging cable maneuverability being 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; however, the cost could outweigh the benefits.

4.6.5.4 Battery Swap-Out Station Design

A battery swap-out station should allow a BEV to enter, be charged by an instructed person, 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 differences associated with 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 need to be evaluated against geotechnical and hydrogeological conditions, similar to any other area in the mine
- Some purpose-built excavations can require special attention to stage charged and receive discharged batteries
- Safety considerations such as egress space around the batteries

- Off-Board Charging of Off-Board Batteries (Battery Swapping), Section 7.5.3

Refer to mine site guidelines and local regulations for safety guidance associated with cranes and battery swaps.

Table 4.1. Pre-installation Considerations for the Charging Area

Characteristics of the area	• Ventilation/cooling system (e.g., recirculated air to avoid filter replacement) • The area should be away from hazardous areas (e.g., diesel storage, high methane areas) • Adequate space for personnel to safely operate and maintain • Early detection and monitoring systems to mitigate battery fire risk • Remote emergency off switch near the charger outside potential hazard zone • Clearly identified parking spaces for BEVs • Location free of water and/or mud due to electrical hazards and should include protection against ingress of dirt and water that could enter charger connectors • Protection of charge cable from abrasion (e.g., a retractable cable) • Adequate visibility and lighting of battery charger controls • Level floors that can be easily cleaned (concrete if possible)
Electrical	• Upstream, overcurrent protection device to supply the charger • Upstream or integrated earth leakage/ground fault protection device (ground fault circuit interrupter) • Upstream, overcurrent protection device to supply the charger • Ground path – Charger is tied to mine ground grid – When plugged in, BEV frame/chassis has a path to ground via charge cable – The DC power needs to be isolated from ground and monitored for safety
Overall	• The overall system should take an evolving mine environment into consideration (e.g., the charging system might need to be easily relocatable multiple times through the mine life without special handling or care) • Compatibility with planned type of charging system (e.g., fixed, cable connected/temporary, or fixed for operation but easily transported to other areas) • Strategies such as whether to install power electronics in a dedicated charger or electrical room or moving the charger around

4.6.5.5 Remote Battery Swapping

Instead of swapping batteries at a charging station, it can be advantageous to swap batteries where the BEVs are working. This method 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. Remote battery swapping can add complexity and cost for procuring, maintaining, and operating the additional equipment, but it can also be beneficial if the distance from the work 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. This method should be considered as part of a sustaining capital for mines using battery swapping technology and expanding above threshold.

4.6.5.6 Mine Power Distribution Considerations

Because most chargers operate with an incoming voltage of 400–1,000 V in three phases, the distribution equipment should be located within an acceptable distance (i.e., 75 m for 600 V) from the chargers to confirm system strength. Because chargers are harmonic producing devices, a stiff system—with high available fault power and good voltage regulation—is ideal for the operation of multiple devices without interference. Generally, 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 might 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.

• Incoming Power System (Charging Systems), Section 7.4

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. In an all-electric mine, the operation of chargers should be considered when sizing a transformer. It is important to keep in mind the charging philosophy to prevent oversizing transformers.

For further guidance on power distribution, peak load, and electrical balance of plants, it is recommended to consult local regulations.

4.6.5.7 Fast Charging Considerations

Due to the large size of mining equipment and 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 should 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 can prevent overloading the mine's electrical system. It is crucial to monitor the amount of heat generated during this process, both inside the vehicle and at the charging site.

4.6.6 Charging System 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 should be stopped immediately to prevent arcing and lethal shocks.

If there is a problem/fault during the charge process (e.g., the battery gets too hot or the cooling system is not working), the vehicle charge control unit should report to the charger and stop the charging. In addition to the BMS, the charger should 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.

- Battery Management System, Section 6.3.1
- Operation and Controls (Charging System), Section 7.6

Maintenance and pre-operational inspections should be performed according to the OEM and charger manufacturer recommendations.

Training programs are also essential in order to safely operate the charging system and avoid collisions and pedestrian interactions in the charging area.

4.7 VENTILATION AND COOLING

The ventilation/cooling systems (e.g., air quality, humidity, noise, and maintenance) will benefit the most by the implementation of an electric fleet. However, a ventilation study should be conducted to 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 should 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 include considerations of temperature, dust, and air velocity targets. However, because of the elimination of diesel, some aspects of the criteria such as DPM regulations might not be required.

Designs are based on battery limits and on 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 4.2 and 4.3).

For specific examples of the ventilation-related benefits of BEVs, see the following case studies: Halim et al. (2021) "Improvement of Working Conditions and Opinions of Mine Workers When Battery Electric Vehicles (BEVs) Are Used Instead of Diesel Machines – Results of Field Trial at the Kittilä Mine, Finland" and Gyamfi et al (2021) "Development of Strategies to Reduce Ventilation and Heating Costs in a Swedish Sublevel Caving Mine – a Unique Case of LKAB's Konsuln Mine."

Table 4.2. Air Volume Design Data Needs, Sources, and Applications for Electric Equipment

Need	Source	Application
Jurisdictional air quality regulations	Federal, local, and company standard threshold limit values	Drive final air volume and distribution calculations to dilute dust, emissions, and heat generated by mobile fleet
Equipment fleet required throughout affected area or mine	Based on production profile and equipment capacity	Mine heat load and dust calculations Size and number of BEVs can differ from diesel fleet
Motor power and expected duty cycles of equipment	Basic data on equipment data sheet from OEMs Might 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 OEMs based on a variety of operating scenarios	Air volume calculations to dilute heat
Heat loads from charging stations/areas	OEMs	Air volume calculations to dilute heat Heat from charging + heat from equipment = total heat load from equipment
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 and with industrial health dust monitoring programs
Heat load from sources other than equipment (surface temperatures, wall rock, auto compression, groundwater)	Local measurements	Mine heat load calculations Total mine heat load is the sum of all heat sources (equipment and non-equipment) This is the heat that should be manage by the mine ventilation system
For mines that have radon: Radon emanation rate for mines that are yet to be developed and airborne radon concentration for operating mines	Laboratory testing for radon emanation rate Local measurements for airborne radon concentration	Determine air volume to dilute radon and to keep residence time of ventilating air short

Table 4.3. Ventilation Design Data Considerations, Sources, and Applications for Electric Equipment

Need	Source	Application
Required airway opening dimensions	Federal, local, or company guidance	Design infrastructure based on air volume required to manage gases, heat, or dust (whichever is higher)
Make sure air velocities from airway opening and air volumes are 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 work area temperatures too high?

Table 4.3. Ventilation Design Data Considerations, Sources, and Applications for Electric Equipment (continued)

Need	Source	Application
Can additional air volume dilute the heat?	Thermodynamic analysis and modeling	An economic analysis to determine if a refrigeration plant required
Fixed monitoring for dust, gas and/or heat	Federal, local, and/or company guidance and available technology	Depends on mine operator preference and air distribution system type and maintenance needs
Will air be recirculated?	Jurisdictional regulations or company standard	Mandatory if controlled recirculation is part of the ventilation system With zero-emission electric equipment, controlled recirculation can be a solution to reduce total mine volumes as long as contaminant concentration levels are met
Determine hazards that could affect the ventilation infrastructure, ability to rescue personnel, and high risk zones for fire	Risk assessment as per industry or company standards	Address high risks with redesign of mine layouts, infrastructure, and air path and direction

4.7.1 Determining Air Volume

The process for determining air volume for battery-powered mobile equipment is based on heat, dust, and air velocity (Figure 4.3). The sections below describe basic process steps in the ventilation design for an electric mine with some reference to diesel-powered equipment.

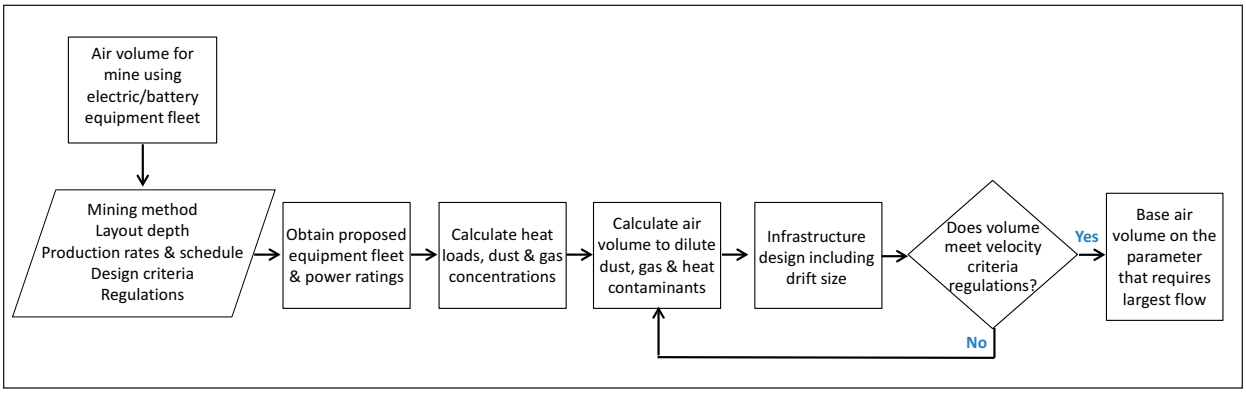


Figure 4.3. High-Level Ventilation Design Process

4.7.2 Regulations

Federal and local (applicable to the mine site jurisdiction) air quality regulations and standards will influence air volume requirements. It should be noted that there are significant variations between jurisdictions, which are continually being reviewed and updated. Only the latest versions of these regulations and associated guidance should be referenced. For example, threshold limit value (TLV) time weighted average (TWA), which is the exposure limit for an eight-hour working shift, is different between jurisdictions for the same contaminant, as shown in Table 4.4. This table also shows that different standards are used by some jurisdictions to measure exposure to DPM. Germany and Australia use elemental carbon, while the Province of Ontario and the USA use total carbon. Internal mining company standards should be determined before beginning mine design. Mobile equipment activities create dust and heat that significantly influence the air volume and the associated distribution. Note that when the working shift is longer than eight hours, the exposure limit should be adjusted accordingly. A common adjustment method is the Brief and Scala model (CCOHS, 2017).

Table 4.4. Examples of TLV TWA of Some Mine Airborne Contaminants in Some Jurisdictions

Contaminant/ jurisdiction	NO_2 (ppm)	CO (ppm)	CO_2 (ppm)	SO_2 (ppm)	Respirable dust (straight concentration, excluding silica content) (mg/m^3)	DPM (mg/m^3)
The European Union (EU)[1]	0.5	20	n/a	0.5	n/a	0.05 (elemental carbon). This will be valid from 21 February 2026 based on the EU directive issued in 2019 [2]
Sweden[3]	0.5	20	5000	0.5	2.5 (inorganic dust)	Currently not available but will be 0.05 (elemental carbon) after 2026-02-21 when the EU limit is enforced
Germany[4]	0.5	20	5000	0.5	1.25 (all dust)	0.05 (elemental carbon). Germany set its limit before the EU, which was done in 2017
Australia[5]	3	30	5000	2	3 (non-coal dust)[6] 2.5 (coal dust)[6]	0.1 (elemental carbon)[7]
Canada (Ontario)[8]	3	25	5000	2	0.9 (bituminous coal dust) 0.4 (anthracite coal dust)	0.4 (total carbon)[9]
USA[10]	5	50	5000	2	1.5 (coal dust)[11]	0.16 (total carbon)[12]
South Africa[13]	3	30	5000	2	2 (coal dust)	n/a

Note that Sweden and Germany (and other EU member countries) are required to follow any limits prescribed by the EU due to their membership in the EU. This is why the limit for NO_2, CO, and SO_2 are the same in Sweden and Germany. The EU currently do not prescribe limit for CO_2, respirable dust, and DPM so each member country has flexibility to determine its limit for these contaminants and other contaminants that are not prescribed by the EU.

1. European Union (EU) Commission (2017)
2. European Union (EU) Commission (2019)
3. Arbetsmiljöverket (2018), which follows the directive from the EU Commission (above), but added values for CO_2 and respirable dust, which are not included in the EU directive.
4. Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA) (2020), which follows the directive from the EU Commission (above), but added values for CO_2 and respirable dust, which are not included in the EU directive.
5. Safe Work Australia (2019)
6. Government of New South Wales (2014)
7. Safe Work Australia (2015)
8. Government of Ontario (2020)
9. Grenier (2017)
10. Mines Safety and Health Administration (MSHA) (2018a)
11. Mines Safety and Health Administration (MSHA) (2018b)
12. Mines Safety and Health Administration (MSHA) (2018c)
13. Stanton et.al. (2014)

4.7.3 Equipment Fleet

The equipment fleet is based on the production profile and is a key parameter for determining mine heat loads. The mine planner should work with the OEM(s) to optimize the fleet and equipment size for the proposed mine layout and production schedule.

- Heat Generation (Performance Standards), Section 9.3.7

4.7.4 Heat Load

The mine heat load is determined by summing 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, wall rock, summer surface climate, and groundwater (if any) for each level. 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 and amount of refrigeration required to manage the heat can be calculated. Because the only emission from a BEV is heat, there is potential to lower the overall mine air volume. The resultant heat loads need to be well understood to avoid elevated temperatures in the work area from reduced air volumes or air velocity. Relevant regulations should be consulted to determine the exact requirements. An analysis that includes all heat sources will typically 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 should be taken to control the quality of information entered into the solvers.

4.7.4.1 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 typically to list the equipment power for both diesel and electric mobile equipment that can be active on the same level at the same time. Factors are then 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 when the engine is loaded or idling. In addition, diesel engines burn fuel on down-ramp travel whereas most BEVs regenerate significant energy back into the battery.

An electric motor's heat generation equals the energy consumed minus the net work done. Load/power profile curves obtained from the OEM would facilitate determining the equipment kW ratings for the heat load determinations.

A heat generation comparison between BEV and diesel equipment was presented at the Mining Diesel Emissions Council (MDEC) in 2018. In this test, two equivalent LHDs performed identical work in an instrumented drift for a length in time. The difference in measured temperatures is illustrated in Figure 4.4 and was quantified further in the full presentation (Armburger, 2018).

Based on the theoretical "efficiency" theory, the BEV should be three times more efficient than the diesel version, however this test run measured a 7.5 times improvement of BEV over diesel with a 0.4°C wet-bulb globe temperature (WBGT) increase versus a 3.0°C WBGT increase.

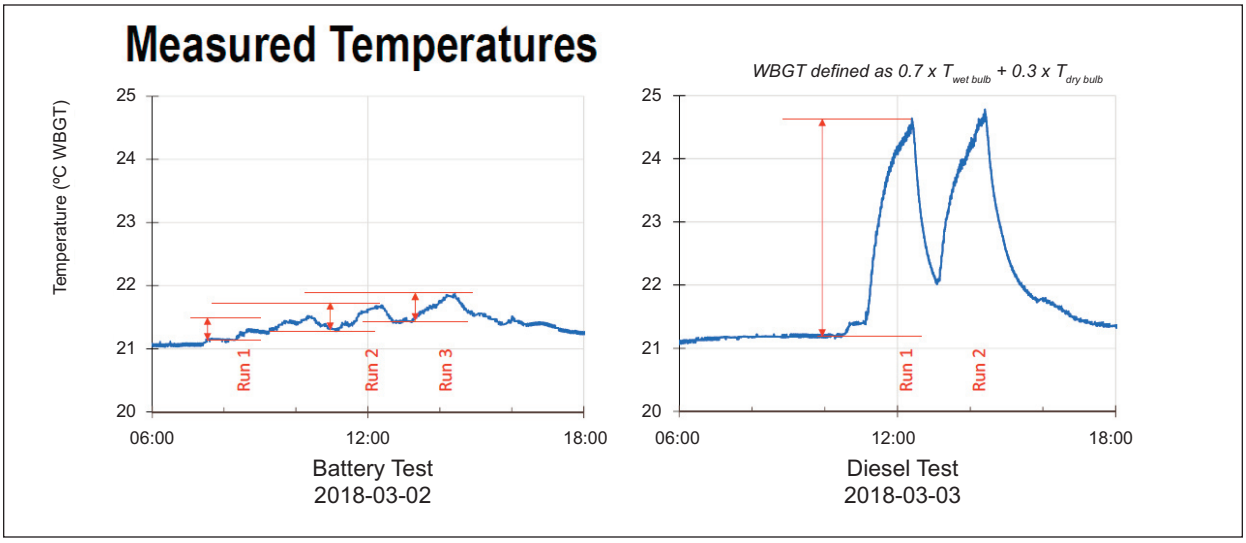


Figure 4.4. Heat Generation Comparison Between BEV and Diesel Equipment (Reproduced with permission from Caterpillar presentation "Direct Comparison of Heat Generation, October 2-4, 2018")

4.7.4.2 Heat From Charging

Typical heat losses from charging equipment are 5–10%, but OEMs and/or charger manufacturers should provide estimates of heat generated when chargers are operating for a given rate and method. Depending on the charging philosophy and placement of chargers, particular attention should be paid to the exhaust path of this heat and placement of infrastructure.

• Incoming Power System, Section 7.4

One 50 kWh charger operating with 5% losses would generate 2.5 kW of heat in the charging area, which can be considered marginal. Four 400 kWh chargers operating in the same area with 10% losses 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 while considering that chargers do not operate 24 h/day. It is crucial to make sure chargers are provided with a reasonable means of cooling so that air temperatures in the charging area remain below the charger manufacturer's specified limits to prevent electronic failures.

4.7.4.3 Heat From Other Sources

Information on determining heat from other sources such as summer surface climate, auto compression, wall rock, and groundwater can be found in McPherson (2009). These sources are not dependent on the type of equipment used, but they should still be managed by the mine ventilation system. Therefore, air volumes and refrigeration requirements in mines that have a high amount of heat from these other sources will be different from mines without them regardless of the use of BEVs.

4.7.5 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, including:

- Large dust particles becoming airborne and causing eye injuries
- Extended exposure to moving air causing eye irritation
- Moving air increasing personnel physical exertion

Air velocities that are too low do not remove and dilute heat or small respirable dust particles, and they can also reduce visibility. Drift size, air volume, and/or recirculation of air should be re-examined in consultation with the relevant local regulatory authorities. Target design air velocities should 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's occupational exposure monitoring program. These data can be used to determine dust sources and concentrations from mining processes and mineralization. Once the air volumes are determined from established target velocities, dilution calculations can determine if the volumes dilute dust concentrations to acceptable levels.

One method to control dust is to prevent it from becoming airborne at the source (e.g., drill rigs, draw points, transfer points, and road surfaces) rather than diluting it with ventilating airflow. Dust is usually suppressed by spraying these sources with water or dust suppressant. Many practitioners agree that ventilation alone is not sufficient enough to manage dust. Supplying too much air volume can worsen the situation due to turbulence in the airflow, which is proportional to the air volume rate and can keep the majority of the dust on-site.

4.7.6 Radon

Airborne radon can be present, not only in uranium mines, but also in non-uranium mines if there is a small amount of uranium in the orebody, or if the groundwater has dissolved uranium in it. Radon needs to be managed adequately because it is a radioactive substance. Making the residence time for ventilating air as short as possible is key to managing radon since hazardous exposure to radon increases with time. The exhaust air from production areas needs to be ejected immediately to the surface and should not be reused in other working areas. Therefore, air volumes for managing radon should be adequate to dilute radon below its local TLV and to keep the residence time short. When the orebody produces significant amount of radon, large air volumes might be required to manage it.

4.7.7 Developing the Ventilation Design and Plan

Conversion to electric equipment at a brownfield mine will be more challenging and require using existing infrastructure (i.e., fans, raises, controls) that is integrated with new infrastructure limiting some opportunity (Figure 4.5). In greenfield mines, the primary ventilation system components such as fans, raises, and transfer drifts can be reduced, as well as auxiliary system fans and ducting. There is also potential to use air heated from chargers, but it needs to be assessed for work area temperature impact and associated hazards identified from the charging activity. If charging occurs during shift change, heated air could be reused for blast clearing and/or to warm cold mine air, but plans should be in place in case of fire and the emission of hazardous gases.

4.7.7.1 Sizing, Placement, and Number of Airways

The air volume requirements will be based on dilution of contaminants (e.g., heat and dust) generated from mining activity. The final ventilation rate is based on controlling the higher emitting contaminates to safe and acceptable levels. 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. Airway placement and quantity are needed in order to consider conditions unique to an electric mine layout such as number and size of substations and charging stations.

Mines that have radon will typically need to excavate more airways (ventilation shafts) than mines that do not have radon in order to keep residence time short.

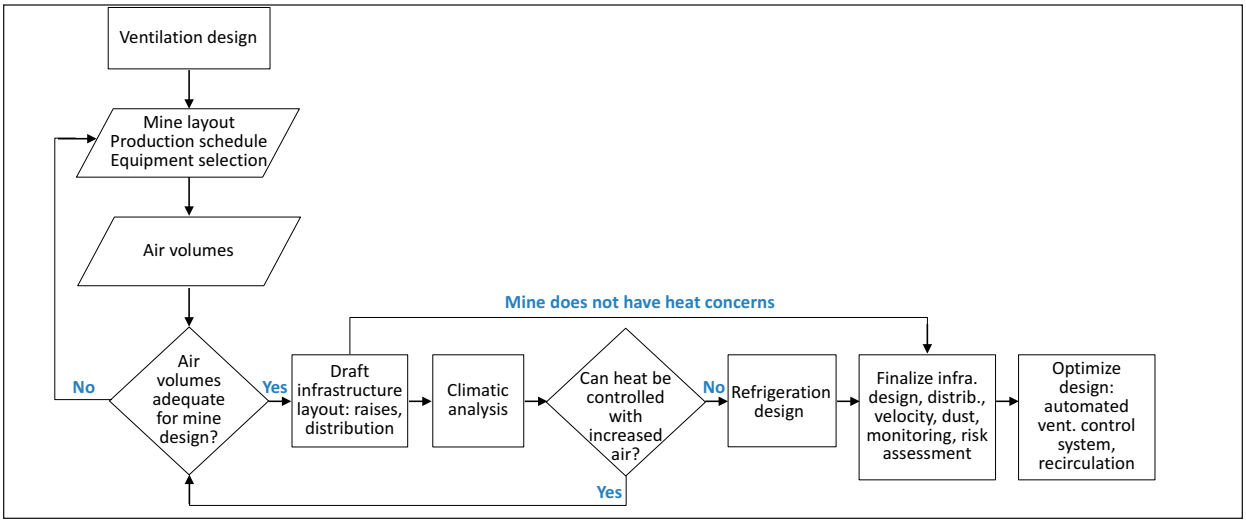


Figure 4.5. High-Level Ventilation Design Process

4.7.7.2 Heat

If the heat load generated in the mine will approach or exceed any design criteria temperature limits (e.g., work area, intake, or reject), a study should be completed to determine if additional air volume can dilute the heat or if mine air cooling is required. Study results will be based on the mine schedule impact and the economics of larger ventilation infrastructure to meet the design temperature criteria versus 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 should be verified to remain within the design criteria limits.

4.7.7.3 Blast Gas Clearing

The time required to clear blasting fumes from the face and through the path to exhaust depends on the air speed. In an electric mine, the opportunity to reduce air volume can create a low air velocity condition, which would extend the blast clearing time and delay personnel reaching the work area. 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, automated ventilation control systems, and ventilation on demand.

4.7.7.4 Monitoring

A mine site should 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 it up to track trends. 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 [CO], sulphur dioxide [SO_2], and nitrogen dioxide [NO_2]). Additional monitoring can also be required based on battery chemistry. CO can be 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 from the barometric pressure. Dust and DPM are currently not commonly measured in real time.

4.7.7.5 Controlled Recirculation

The 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 zero gas emissions, less heat, and generates less dust than the diesel powered equivalent. If controlled recirculation is part of the design, fixed monitoring would be required to confirm regulatory compliance of air quality. Fire risk analysis should be included in this design as well to confirm that in the event of fire, combustion products will not be recirculated into intake airways. It should also be noted that controlled recirculation might not be feasible in mines that have radon.

4.7.7.6 Ventilation for BEVs in Coal Mines

Coal mines will have specific ventilation requirements that replacing diesel vehicles with BEVs will not change. Ventilation design in coal mines is mostly based on diluting methane that is emitted by coal seams to be below the concentration limit prescribed in health and safety regulations. This limit (in % volume) is the safe limit to prevent methane from forming an explosive gas mixture, which is determined by risk assessments and is different between jurisdictions. For example, in the State of New South Wales in Australia, the limit of methane in intake airflow to any development and longwall face is 0.25% (Government of New South Wales, 2014), while in the neighbouring State of Queensland, the limit is 0.5% (Government of Queensland, 2017). In both states, the limit in panel exhaust (return) airway is set at 1% to allow diesel equipment to enter it.

Large equipment in coal mines (e.g., longwall shearers, continuous miners, and belt conveyors) are electric and get their power directly from the mine substation using cables. Small to medium diesel equipment like loaders, personnel carriers, and longwall shield carriers are occasionally used. Air volume that is supplied to dilute methane is usually more than adequate to dilute diesel exhaust emissions, therefore replacing this equipment with BEVs will not necessarily reduce the airflow requirements. In many coal mines, it is not possible to reduce air volume below the maximum capacity of the ventilation circuit due to high methane emission.

4.8 BATTERY AND FIRE SAFETY

- Energy Storage Systems, Safety Requirements, Section 6.4
- Explosion Protection for Gassy Mines, Appendix B

The adoption of BEVs can reduce some potential fire risks by minimizing or removing diesel fuel and hot engine sources of ignition from the underground environment. However, BEVs also present a unique risk to personnel. BEVs can present several battery chemistries and battery designs that require special consideration when a BEV is involved in an incident that structurally damages batteries or causes a vehicle fire.

Relative to the number of rechargeable batteries in active use, LIBs have caused little harm in terms of damage and personnel injury. Battery manufacturers and OEMs achieve this level of safety by adding layers of protection, which include but are not limited to:

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

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

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

Those operating BEVs should consider what equipment health and condition monitoring plans will be required for prevention and early detection of these hazards. Requirements for design adaptations (e.g., fire doors, egress requirements) and personal protective equipment (e.g. oxygen-generating self rescue devices) should also be considered. Fire prevention, mitigation, and response strategies should be developed in consultation with local regulators, insurance providers, and OEMs.

Resources such as the Swiss Federal Department of the Environment, Transport, Energy and Communications DETEC (2020) research report on *Minimizing the risk of electric vehicle fires in underground transport infrastructures* provide further information about infrastructure.

4.8.1 Refuge Station Considerations

When designing to accommodate BEVs, it is necessary to understand the potential for fire and the ease or difficulty to reach personnel if they require rescue.

Refuge stations should be planned in the production and development levels in each of the mining zones to mitigate risks of uncommon gases being released into the ambient atmosphere. These risks will vary depending on the battery make and model. Key gases to consider for BEVs underground are CO and HF, which can both spread throughout mining zones and exceed safe levels and reach dangerous and potentially fatal levels, depending on the duration of exposure.

4.8.2 Emergency Response and Battery Fires

There are unique issues associated with fighting a fire on a BEV, which should be identified (e.g., through special labelling) to protect mine rescue personnel from harm. These include:

- An electric mine changes the form and distribution of energy sources on-board mobile equipment when compared with traditional mines.
- There can be areas where large numbers of equipment are concentrated for charging.

- Fire Hazards and Suppression, (Energy Storage Systems), Section 6.4.4 (covers technical aspects of battery fires in more detail)

While battery electric fires will generally require the same treatment as other fires, fire protocols at the mine need to be revisited to confirm that they incorporate the specific hazards and protocols associated with the battery. For example, 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. Each battery is different, and due to the ongoing evolution of battery chemistry, more studies are required to indicate what contaminants could be or are present in case of fire.

The OEM therefore needs to supply the fire scenarios and specialized safety measures for the types of batteries they are providing. Based on these scenarios, protocols for fire response need to be incorporated in the mine design. Table 4.5 describes some key issues that should be considered before any BEV is introduced into the mine.

Detailed guidance on fire rescue will vary depending on jurisdiction. Some references from the United States include the National Fire Protection Association recommendations for response to BEV fires from LIBs (Long & Blum, 2016; Mikolajczak, 2011) and an online course (National Fire Protection Association, 2018). Ontario Mine Rescue also provides some guidance on underground battery fire hazards and emergency response (Rulli, 2020).

4.9 TRAINING

All personnel working with or around a BEV should be properly trained to fully understand the operational differences, make sure safe practices are used, and identify and avoid potential hazards. A brief summary of examples of training needs for different roles is provided in Table 4.6, but it is not intended to be exhaustive.

Table 4.7 lists standards that could be used as a starting point and general guidance to design an appropriate training program for both maintenance and operations personnel. Please note that these standards are not necessarily specific to mining BEVs and do not apply to all situations.

Table 4.5. Emergency Response Considerations

Are the battery chemistry and fire suppression techniques understood for this BEV?	• Is the BEV equipped with an appropriate fire extinguisher? • Are the operators trained in the appropriate response to a fire on-board? • Is the appropriate personal protective equipment (PPE) available (refer to manufacturer's instructions)? • Are emergency services aware of the proper fire suppression techniques? • Do emergency services have the appropriate training to fight a fire on this BEV? • Do emergency services have the appropriate fire suppression equipment? • Do emergency services understand the time required for the fire to burn out? Please note, requirements vary between jurisdictions, so it is important for owners to consult with local emergency services.
In mixed fleets, emergency personnel might have to quickly identify the battery chemistry on-board a given BEV and choose the appropriate suppression technique.	• Can emergency personnel quickly identify the battery chemistry from a distance during an emergency? • Have operators been trained to identify the battery chemistry and any unique responses they should take based on that chemistry?
Fires and structural damage will likely lead to a cleanup operation later.	• Are mine maintenance personnel aware of the battery chemistry on-board the BEV? • Do maintenance personnel have access to the appropriate equipment to clean up after a chemical spill from the BEV? • Do mine maintenance personnel have the proper training to safely clean up after a battery chemical spill?

Table 4.6. Examples of Training Needs for Personnel Associated with BEVs (non-exhaustive)

Role	Training Requirements
Operators	Some training on the battery user interface, power and drive systems, charging systems, battery chemistry and safety, and machine-specific safety considerations (e.g. where high- and low-voltage areas are, how to isolate by lock out and tag out as well as other procedures for capacitance discharge)
Mechanics	General training 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)
Battery maintainers	Battery maintenance will either be handled by the OEM or the mine and requires additional skillsets
Remote service/support	Additional skillsets might be required when troubleshooting, perhaps direct towards OEMs and/or engineers
Mine rescue personnel	Training on differences in addressing fire risks associated with BEVs
All personnel	All personnel need to be trained to conduct the chosen charging method

4.9.1 Operator Training

Operator manuals should be provided by the OEM; additional training options can potentially be available. Charger training might need to be covered more in depth and be provided by the charger manufacturer if the charging is done off-board by a third party supplier.

Typical BEV operational practices that can differ from a diesel equivalent include:

- Daily inspections (e.g., looking for frayed wires, damaged cables)
- Unit start-up
- Brake test procedures
- Emergency procedures

- Accommodation of performance differences, such as:
  - Lower noise levels (BEV design should incorporate warning sounds that can be triggered manually, such as a horn, or automatically for BEVs travelling in forward or reverse)
  - Higher torque output and quicker acceleration
  - Higher maximum speed
  - Regenerative braking
- Procedures for removing BEVs due to malfunction or loss of power (the OEM is responsible for providing such procedures)

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. Regeneration of energy into the battery can play a role in planning out what charge the battery should receive to avoid tramming down-ramp with a full battery. Relative to refuelling with diesel, BEVs have a shorter tramming range or working time between charges and take longer to charge or swap the battery. Operators should have an understanding of the energy required to complete a specific task to make sure the charge level is sufficient or make the decision to charge the unit before proceeding. Range and regeneration performance estimates from the OEM and training can assist the operator with determining how to proceed.

- Charging System Operation and Maintenance, Section 4.6.6
- Definitions (Performance Standards), Section 9.2 (describes duty cycle planning and availability and utilization)
- Maintenance Areas, Section 4.3
- Charging System Operation and Maintenance, Section 4.6.6
- Maintenance and Service Areas on the Equipment, Section 5.9

4.9.2 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 equipment.

Table 4.7. Examples of Standards Related to BEV Operator and Maintenance Personnel Training

Standard	Topic	Jurisdiction	Citation
ISO 14990-1 – *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 1: General requirements*	See Section 15.7 for maintenance manual and service literature, including reduction of electrical hazards while servicing a BEV. This standard applies to electric equipment, not specifically to mining BEVs.	International	International Organization for Standardization, 2016a
ISO 20474-1 *Earth-moving machinery—Safety—Part 1: General requirements*	Specifies appropriate technical measures for eliminating or reducing risks from relevant hazards, hazardous situations, or events during commissioning, operation, and maintenance. This is a general standard and reference for good practice but not specific to mining BEVs.	International	International Organization for Standardization, 2017d
ISO 8152 *Earth-moving machinery—Operation and maintenance—Training of mechanics*	Training of mechanics appropriate for earth-moving machinery. Not specific to BEVs.	International	International Organization for Standardization, 1984
ISO 6750 *Earth-moving machinery — Operator's manual — Part 1: Contents and format*	Specifies the content and gives guidance on the format of operators manuals for earth-moving machinery. For reference only as many organizations would also have internal standards.	International	International Organization for Standardization, 2019b
ISO 7130 – *Earth-moving machinery—Operator training—Content and methods*	Basis for content and methods used for operator training for earth-moving machinery. This standard is a reference for making sure there is sufficient operator training and safety.	International	International Organization for Standardization, 2013

4.10 RISK ASSESSMENT

Introducing BEVs into the mining environment can introduce new risks, reintroduce once well managed risks, and further mitigate other already controlled risks in underground mining. The risk assessment is therefore a key part of operational planning.

In each of the sections within this guideline, potential risks are identified with suggested controls for the mining business, mine design and operations, BEV design, energy storage systems, and charging systems. Although controls are suggested in most cases, this guidance is not considered to be exhaustive. This subsection intends to help consolidate guidance on what to consider when developing a risk management framework for the adoption of BEVs in mining. It summarizes the risk presented in other sections in a table format to help guide a risk assessment. The risks are not evaluated in this document because the end user is expected to use their risk management toolset to analyze, evaluate, and categorize the risk treatment. It is not possible to provide defined risk outcomes because every instance of BEV installation will have unique risks and challenges that need to be evaluated with appropriate risk treatment applications.

4.10.1 Financial, Production, Health and Safety, and Environmental Risks

Risks can be categorized into at least four categories:

- Financial or business risks where the capital or operating expense profile is negatively impacted due to the changes required to support BEV fleets (Table 4.8).
- Production risks where the overall productivity is impacted due to negative impacts on equipment utilization or availability (Table 4.9).
- Health and safety risks where BEV equipment and infrastructure present risk to personnel (Table 4.10).
- Environmental risks where the byproducts can adversely impact the natural environment (Table 4.11).

A risk assessment team can have more or differing categories depending on the approach taken.

Table 4.8. Financial Risk Considerations

Risk	Risk Source	Possible Treatment
Increased infrastructure capital expense	• Larger capacity power infrastructure • Charging infrastructure • Battery handling infrastructure • Service upgrades • Battery procurement • Electric vehicle premiums	• Mine design optimized for BEV • Mine energy management system • Optimized charging philosophy and control • Lease versus own battery • Capital reduction or ventilation and fuel infrastructure
Increased operating expense	• Increased power demand • Decrease in production rate	• Optimize charging philosophy and control • Decrease power demand for ventilation & refrigeration • Increase in performance compared to diesel when operating • Fast charge • Battery swap • Opportunity charging • Reduced equipment (mobile platform) maintenance
Early battery replacement	• Overdischarge • High or low temperature charging/discharge • Overcharge	• Battery monitoring system • Selected battery chemistry • Battery maintenance program • Battery lease programs

Table 4.9. Production Risk Considerations

Risk	Risk Source	Possible Treatment
Production rate impact (utilization, availability)	• Battery charging time • Charger availability	• Mine design optimized for BEV • Charger location optimized • Energy management system • Optimized charging philosophy and control • Lease versus own battery • Opportunity charging

Table 4.10. Health and Safety Risk Consideration

Risk	Risk Source	Possible Treatment
Discharged vehicle recovery	• Battery failure • Discharged battery • Battery lifecycle near end • Operator error	• Provide available charging at deeper elevations • Towing disabled vehicle plans • Charging vehicle to vehicle • Optimize charging locations to match haulage patterns • On-board charging to common equipment plugs • Opportunity charging • Battery monitoring system • Reserve capacity for recovery mode
Early battery replacement	• Overdischarge • High temperature • Overcharge • Frequent under charge	• Battery monitoring system • Selected battery chemistry • Battery maintenance program • Battery lease programs
Fire/explosion	• Battery failure • Short-circuit • Overcurrent • Overcharge • Excessive charge rate • Excessive regeneration • Thermal runaway • Collision/impact/puncture	• Battery chemistry selected • Battery monitoring system • Short-circuit protection • Overcurrent protection • Wiring methods • Protection from puncture • Arcing faults • Firefighting plan • Remote machine monitoring • Fire suppression • Design quality and redundant controls
Asphyxiation	• Battery/vehicle fire • Immediately dangerous to life or health (IDLH) levels of toxic combustion products	• Battery chemistry selected • Automatic fire suppression systems • Mine design/location of concentrated battery storage, parking, or charging locations • Protections against fire/explosions above • Mine ventilation design • Fire door/containment in concentrated battery locations • Oxygen generating self rescue devices
Electric shock	• Exposed live electrical parts • Damaged battery • Damaged wiring/charging cable • Faulty charger • Faulty/damaged connector/plug • Battery cannot be de-energized • Open bus on trolley assist	• Battery isolation • Work methods and PPE • Insulated tools • Insulated covers/blankets • Charger isolation • Charger control system • Earth fault protection • Resistance grounding limiting current less than 35 mA (AC) • Open bus height/protective insulation • Isolated poles/earth fault detection • Design quality and redundant controls
Arcing fault (burns, arc explosion)	• Same as electrical shock	• Short-circuit protection • Overcurrent protection • Arc fault detection • Battery isolation • Work methods and PPE
Equipment runaway	• Battery overcharge • Excessive regeneration • Faulty/damaged/overheated resistor	• Spring applied hydraulically released/fail-safe braking systems • Braking resistor and cooling • Optimized charging philosophy

Table 4.10. Health and Safety Risk Consideration (continued)

Risk	Risk Source	Possible Treatment
Noise (lack of)	• No diesel motor	• Lighting/marking lights/strobe lights • Beacon • Collision avoidance systems • Personnel alert systems • Audible alarm

Table 4.11. Environmental Risk Considerations

Risk	Risk Source	Possible Treatment
Worn battery skulls toxic to environment	• Old batteries	• Battery chemistry selected • Recycling program with manufacture/lease arrangement
Electrolyte leakage	• Damaged batteries	• Battery design with secondary containment • Battery maintenance program

4.10.2 Risk Management Tools

There are many risk management techniques available to document, classify, and categorize risk such as HAZOP (hazard operability), HAZAN (hazard analysis), HAZID (hazard identification), and SWOT (strengths, weaknesses, opportunities, and threats). The technique can depend on the stage of the design/implementation process and is an integral part of the overall safety management system. Tools such as bowtie, root cause, fishbone, and event chain help to categorizes, rank, and evaluate the effectiveness of controls. These techniques and tools listed are not exhaustive and intended only to inform the reader of multiple options; it is expected the techniques and tools of choice will be used to evaluate risk in managing the introduction of a BEV fleet. For further reference, see https://www.ispatguru.com/hazard-hazid-hazan-and-hazop-part-of-safety-and-risk-management/.

Risk management treatments attempt to reduce risk by applying a hierarchy of controls and mitigations impacting either the consequence (severity) or likelihood (probability) of a risk event. The more effective the control, the greater the impact for the safety management program. The risk treatments listed above can be classified within the hierarchy of controls to enable effective management (NIOSH, 2015). Having lower layers backing up more effective controls further enhances the overall effectiveness. Standards such as ISO 31000 and ISO 12100 can be used for further guidance and developing an overall change management plant with effective risk controls.

SECTION REFERENCES

Arbetwmiliöverket. (2018). *1 Hygieniska gränsvärden* [Health and safety] (Publication No. AFS 2018:1) https://www.av.se/globalassets/filer/publikationer/foreskrifter/hygieniska-gransvarden-afs-2018-1.pdf

Armberger, Jay (2018). *Battery vs diesel—Underground LHD's direct comparison of heat generation* [Conference Presentation]. MDEC 2018, Toronto, ON, Canada. https://mdec.ca/2018/

Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BauA). (2020). *Technische Regeln für Gefahrstoffe (TRGS) 900 Arbeitsplatzgrenzwerte* [Technical Rules for Hazardous Substances (TRGS) 900 Occupational Hazard Limits] (Publication No. TRGS 900). https://www.baua.de/DE/Angebote/Rechtstexte-und-Technische-Regeln/Regelwerk/TRGS/TRGS-900.html

The National Institute for Occupational Safety and Health (NIOSH). (2015, January). *Hierarchy of Controls.* https://www.cdc.gov/niosh/topics/hierarchy/default.html

Canadian Centre for Occupational Health and Safety (CCOHS). (2017, February). *Occupational Hygiene—Occupational Exposure Limits*. https://www.ccohs.ca/oshanswers/hsprograms/occ_hygiene/occ_exposure_limits.html

CSA Group. (2016). *Use of electricity in mines* (Standard No. M421-16[R2016]). CSA Group. https://www.csagroup.org/store/product/M421-16/

European Union Commission. (2014). *Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits.* Official Journal of the European Union, L 96, 357–374. https://eur-lex.europa.eu/eli/dir/2014/35/oj

European Union Commission. (2017). *Establishing a fourth list of indicative occupational exposure limit values pursuant to Council Directive 98/24/EC, and amending Commission Directives 91/322/EEC, 2000/39/EC and 2009/161/EU* (Text with EEA relevance). (Commission Directive (EU) 2017/164). Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017L0164&from=EN

European Union Commission. (2019). *Directive (EU) 2019/130 of The European Parliament and of The Council of 16 January 2019 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work.* Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0130&from=FR

Government of New South Wales. (2021). *Work Health and Safety (Mines and Petroleum Sites) Regulation 2014.* https://legacy.legislation.nsw.gov.au/~/pdf/view/regulation/2014/799/whole

Government of Ontario. (2020). *Current Occupational Exposure Limits for Ontario Workplaces Required under Regulation 833* (Publication No. ON Reg 833/20) https://www.labour.gov.on.ca/english/hs/pubs/oel_table.php#qr

Government of Queensland. (2021). *Coal Mining Safety and Health Regulation 2017.* https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2017-0165

Grenier, M. (2017). *Diesel Particulate Matter–Limits of Exposure and Exposure Data.* Lung Cancer and Prevention in Mining [Symposium Presentation]. Natural Resources Canada, Sudbury, ON, Canada. http://www.occupationalcancer.ca/wp-content/uploads/2017/03/GRENIER-2017.pdf

Gyamfi, S., Halim, A., and Martikainen, A. (2021). Development of Strategies to Reduce Ventilation and Heating Costs in a Swedish Sublevel Caving Mine – a Unique Case of LKAB's Konsuln Mine. *Mining, Metallurgy & Exploration.* https://doi.org/10.1007/s42461-021-00483-y

Halim, A., Lööw, J., Johansson, J., Gustafsson, J., van Wageningen, A., and Kocsis, K. (2021). Improvement of Working Conditions and Opinions of Mine Workers When Battery Electric Vehicles (BEVs) Are Used Instead of Diesel Machines – Results of Field Trial at the Kittilä Mine, Finland. *Mining, Metallurgy, and Exploration*. https://doi.org/10.1007/s42461-021-00506-8

International Organization for Standardization. (1984). *Earth-moving machinery—Operation and maintenance—Training of mechanics.* (Standard No. ISO 8152:1984). https://www.iso.org/standard/15235.html

International Organization for Standardization. (2010). Safety of machinery — General principles for design — Risk assessment and risk reduction (ISO 12100:2010). https://www.iso.org/standard/51528.html

International Organization for Standardization. (2013). *Earth-moving machinery—Operator training—Content and methods* (Standard No. ISO 7130:2013). https://www.iso.org/standard/55300.html

International Organization for Standardization. (2016a). *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 1: General requirements* (Standard No. ISO 14990-1:2016). https://www.iso.org/standard/63299.html

International Organization for Standardization. (2017d). *Earth-moving machinery—Safety—Part 1: General requirements* (Standard No. ISO 20474-1:2017). https://www.iso.org/standard/60734.html

International Organization for Standardization. (2018). *Risk management — Guidelines* (ISO Standard No. 31000:2018). https://www.iso.org/standard/65694.html

International Organization for Standardization. (2019b). *Earth-moving machinery — Operator's manual — Part 1: Contents and format* (Standard No. ISO 6750-1:2019). https://www.iso.org/standard/68900.html

Long, T. R., & Blum, A. (2016) *Lithium ion batteries hazard and use assessment—Phase III.* National Fire Protection Association. https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Research-reports/Hazardous-materials/Lithium-ion-batteries-hazard-and-use-assessment

McPherson, M.J. (2009). *Subsurface Ventilation Engineering.* Mine Ventilation Services, Inc. https://www.srk.com/en/publications/subsurface-ventilation-engineering-book-published-paper

Mikolajczak, C., Kahn, M., White, K., & Long, R. T. (2011). Lithium-ion batteries hazard and use assessment. National Fire Protection Association. https://www.nfpa.org/News-and-Research/Data-research-and-tools/Hazardous-Materials/Lithium-ion-batteries-hazard-and-use-assessment

Mine Safety and Health Administration (MSHA). (2018a). *Title 30 Mineral Resources.* Code of Federal Regulations (CFR). Part 7 subpart E Diesel engines intended to be used in underground coal mines regulation 7.84, pp. 32. https://www.govinfo.gov/content/pkg/CFR-2018-title30-vol1/pdf/CFR-2018-title30-vol1.pdf

Mine Safety and Health Administration (MSHA). (2018b). *Title 30 Mineral Resources.* Code of Federal Regulations (CFR). Part 70 subpart B Dust standards regulation 70.100, pp. 454. https://www.govinfo.gov/content/pkg/CFR-2018-title30-vol1/pdf/CFR-2018-title30-vol1.pdf

Mine Safety and Health Administration (MSHA). (2018c). *Title 30 Mineral Resources.* Code of Federal Regulations (CFR). Part 57 subpart D Air quality, radiation, physical agents, and diesel particulate matter, regulation 57.5060, pp. 372. https://www.govinfo.gov/content/pkg/CFR-2018-title30-vol1/pdf/CFR-2018-title30-vol1.pdf

National Fire Protection Association (n.d). *Energy storage systems and solar systems safety online training* [Training Course]. https://catalog.nfpa.org/Energy-Storage-and-Solar-Systems-Safety-Online-Training-P21165.aspx

Paraszczak, J., & Svedlund, E., Fytas, K., & Laflamme, M. (2014). *Electrification of Loaders and Trucks – A Step Towards More Sustainable Underground Mining.* Spain, *RE&PQJ* 1(12), 88-86. https://doi.org/10.24084/repqj12.240

Rulli, Dan (2020, February 12). *Ontario Mine Rescue: Emergency Response to Battery Fires* [Conference Presentation]. Battery Electric Vehicle Safety in Mines, Workplaces Safety North, Sudbury, ON., Canada. https://www.workplacesafetynorth.ca/resources/one-day-symposium-battery-electric-vehicle-safety-mines

Safe Work Australia (2015). *Guide to Managing Risks of Exposure to Diesel Exhaust in the Workplace.* https://www.safeworkaustralia.gov.au/system/files/documents/1702/guidance-managing-risks-exposure-diesel-exhaust-in-the-workplace.pdf

Safe Work Australia (2019). *Workplace Exposure Standards For Airborne Contaminants.* https://www.safeworkaustralia.gov.au/system/files/documents/1912/workplace-exposure-standards-airborne-contaminants.pdf

Stanton, D.W., du Plessis, J.J.L., Belle, B.K. (2014). Occupational Exposure Limits for Airborne Pollutants, In duPlessis, J.L.L (Ed.), *Ventilation and Occupational Environment Engineering in Mines* (pp. 237-254). Mine Ventilation Society of South Africa, Johannesburg.

Swiss Federal Department of the Environment, Transport, Energy and Communications DETEC. (2020). *Minimizing the risk of electric vehicle fires in underground transport infrastructures* [Publication No. FB1678]. https://www.mobilityplatform.ch/de/research-data-shop/product/1678

United Nations (2015). *Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train* (Standard No. E/ECE/324/Rev.1/Add.82/Rev.5). https://op.europa.eu/en/publication-detail/-/publication/fd8e6b47-d767-11e4-9de8-01aa75ed71a1

Willick, Dave (2011). *Underground Electric Haulage Trucks Introduction and Benefits,* MDEC. https://mdec.ca/2010/S3P3_willick.pdf

5. BATTERY ELECTRIC VEHICLE DESIGN

5.1 INTRODUCTION

In addition to electric traction motor(s), BEVs comprise of an operator interface, braking system, electrical system (including the battery and BMS), and in some cases, an on-board charging system. Depending on the design, a given BEV can use: a transmission; a clutch, gearbox, differential, and fixed gearing; and battery packs and motors (Figure 5.1). Overall, the BEV design should integrate a strong relationship between the design of the electric motor and other BEV components.

Throughout this section, several standards are referenced by standard number. Table 5.1 at the end of this section lists the standards in the order they first appear and provides further information, including the title, description, and a citation.

This section includes information about the systems and components of a BEV and their design and use, summarized in the navigation below.

- Equipment Performance (Performance Standards), Section 9.3
- BEV General Information Form, Appendix C (an example of the types of information an OEM could provide about the design of the BEV)

General note on safety content in this section

Safety encompasses all components of the BEV for the full lifecycle, from commissioning to decommissioning and is considered throughout this Section (see the navigation table below). Functional safety standards (e.g., ISO 13849, ISO 19014, and IEC 61508) cover overall risk assessments.

Braking System (Section 5.2) Outlines recommended considerations for dynamic braking and provides guidance on secondary braking systems.

⚠ Includes some information about managing unsafe conditions associated with braking systems and cites relevant standards.

HVDC Electrical System (Section 5.3) Discusses the high-voltage DC (HVDC) distribution system for the overall vehicle.

⚠ This section has a strong safety focus, covering the safety risks associated with HVDC systems, providing guidance on their mitigation and management in BEV design, and referencing relevant standards. The risks covered include short-circuiting, electric shock, arc flash, overcurrent protection, insulation and ground fault monitoring, and isolation and service disconnect.

Low Voltage and Control System (Section 5.4) Discusses low-voltage components of BEVs and control systems, including information on low-voltage distribution and control, high-voltage interlock loop (HVIL), master disconnect, emergency stop, operator interfaces, software and firmware, and remote control.

⚠ This section has a strong safety focus, identifying ways in which controls are designed for safety and to mitigate hazards and failures.

Electrical and Radio Interference (Section 5.5) Outlines precautions needed to be sure that BEVs do not adversely affect nearby equipment, communication devices, or other microprocessor-controlled devices.

⚠ Identifies the risk of interference associated with blasting caps as a particular concern.

Drivetrain (Section 5.6) Outlines the drivetrain components and design specific to BEVs.

⚠ Content does not specifically focus on safety, but components are designed for safe operation.

Fire Safety (Section 5.7) A brief section that guides the reader very generally on what to think about regarding fire safety.

⚠ The key recommendation is for the vehicle to be designed in alignment with local legislation so that any vehicle fires should not propagate to the battery.

Shock and Vibration (Section 5.8) A brief section that guides the reader very generally and references relevant standards.

⚠ The key recommendation is that the BEV should be designed to meet shock and vibration profiles that align with the anticipated use environment.

Maintenance and Service Areas on the Equipment (Section 5.9) Describes considerations related to components, enclosures and covers, and service areas in the BEV design.

⚠ Most considerations in this section focus on designing these areas so that they can be accessed and maintained safely (e.g., to prevent contact with high voltage or other hazards).

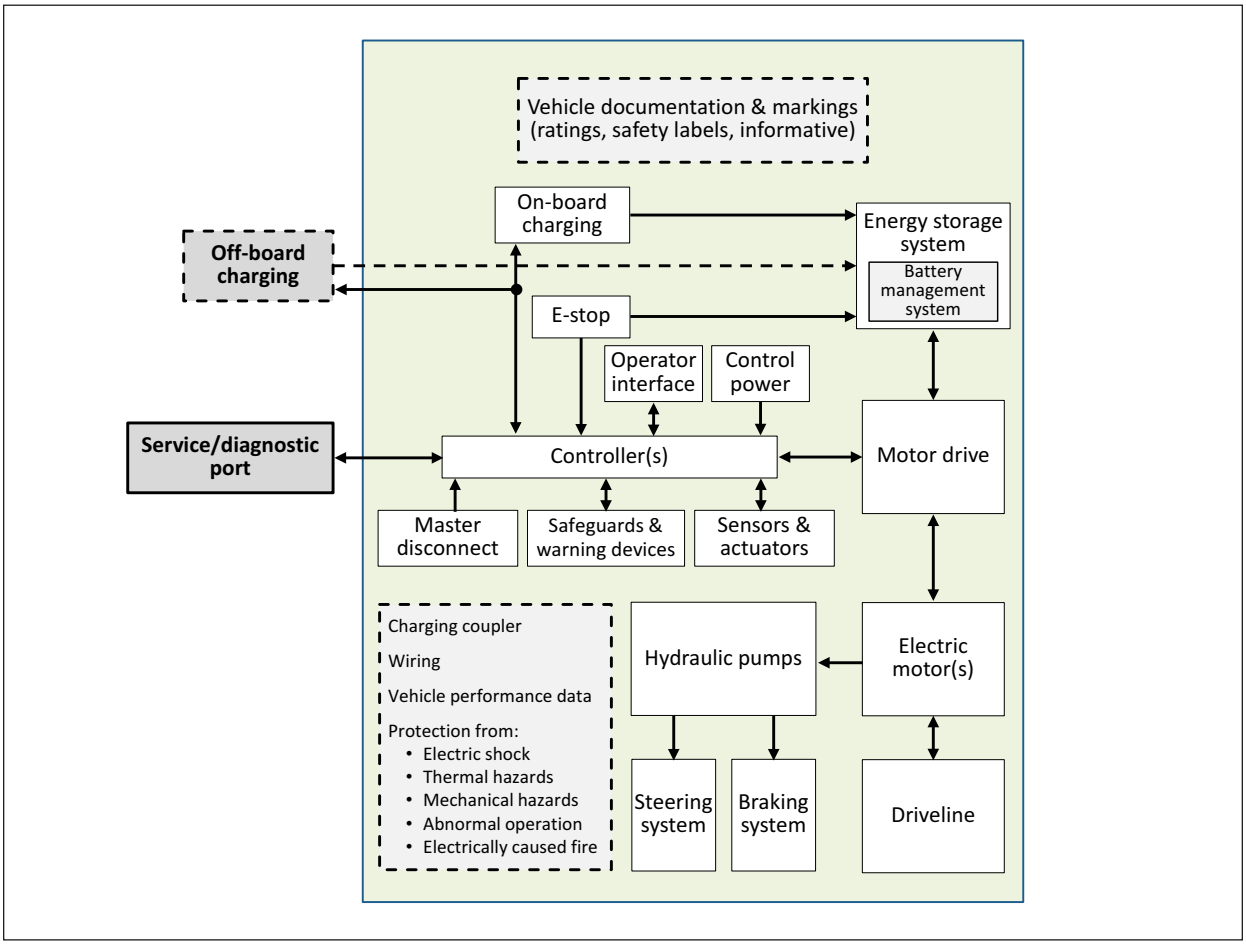


Figure 5.1. Representative BEV Block Diagram. Some functions are not indicated for simplicity.

5.2 BRAKING SYSTEM

The vehicle is generally required to have a service brake system, a secondary braking system, and a park brake system as defined in ISO 3450 and CAN/CSA-M424.3-M90 or other applicable standard.

See the **Glossary** for a list of definitions.

The following should be noted regarding dynamic braking:

- Rheostatic braking should have the capacity to dissipate the braking power. Given the current state of the technology, this is typically accomplished by the use of grid

- Regenerative Braking and Ramp Design, Section 4.2.2
- Equipment Performance, Regenerative Braking, Section 9.3.3

brake resistors. Depending on the design strategy, rheostatic brakes might need to be combined with service brakes or adjusted to accommodate larger vehicles.

- Regenerative braking using batteries requires a reserve battery capacity in which energy can be returned to the battery by the supply line. Regenerative braking 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.
- The regenerative brake limits, shortfalls, and traction motor are affected by the battery system.
- 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 vehicle 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 needs to 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, loss of motor braking torque should automatically apply the secondary braking system in compliance with ISO 3450 and CAN/CSA-M424.3-M90 or other appropriate standards. The secondary braking system should be applied automatically following the activation of a warning after the system senses an unsafe condition from the BMS, or vehicle control system in conjunction with CAN/CSA-M424.3-M90 or other appropriate standards. The braking system circuit should be designed in accordance with ISO 13849-1 and tested in accordance with ISO 13849-2, ISO 3450 and CAN/CSA-M424.3-M90, or other appropriate standards.

5.3 HVDC ELECTRICAL SYSTEM

The function of the high-voltage DC (HVDC) distribution system is to safely transfer electrical energy from the vehicle's batteries to the various loads, such as the drivetrain, hydraulic systems, DC/DC converters, and other powered devices that can be on-boarded. In addition, the HVDC system should also have a provision for charging the batteries.

The term high voltage is not universally defined and can vary between jurisdictions as well as between industries and trades. For the purposes of this document, high voltage refers to the nominal voltage produced by the main batteries on-board the vehicle, which typically ranges from 200 to 1000 VDC.

The HVDC distribution system is critical to the safe operation of the vehicle. A well designed system manages the flow of the electrical currents to the loads and responds appropriately to abnormalities such as overloads or short circuits. It is similar to any utility distribution system used in fixed industrial or commercial applications. Given the typical capacity of the energy storage system on-board a mining BEV, the available electrical energy can be comparable to portions of a fixed plant distribution system.

The HVDC distribution system needs to be designed and installed in accordance with sound electrical engineering practices and by a team of competent electrical designers and engineers. A poor design or execution can result in electric shock, arc flash, or a vehicle fire. It is advisable to ultimately have an experienced licensed engineer review, approve, and take responsibility of the overall HVDC design in accordance with local professional engineering practice and regulations.

The risk of exposure to electric shock and arc flash should be observed and analyzed. Batteries are stored energy systems and the means by which operators and technicians are prevented from inadvertent exposure should be considered. A process of identification, assessment, and control implementation should be executed during the design phase of BEVs with respect to high-voltage exposure. Using risk control methods, the vehicle lockout and safe shutdown procedure should be well defined so that operators and technicians have an effective procedure that they can refer to with confidence.

Electrical systems should be designed in accordance with ISO 14990-1, ISO 14990-2, and ISO 14990-3 or other applicable standards. Applicable local codes should also be reviewed and followed.

5.3.1 Direct Current (DC) System Architecture

Figure 5.2 provides an overall visual of DC system architecture. Note that this figure does not include all details.

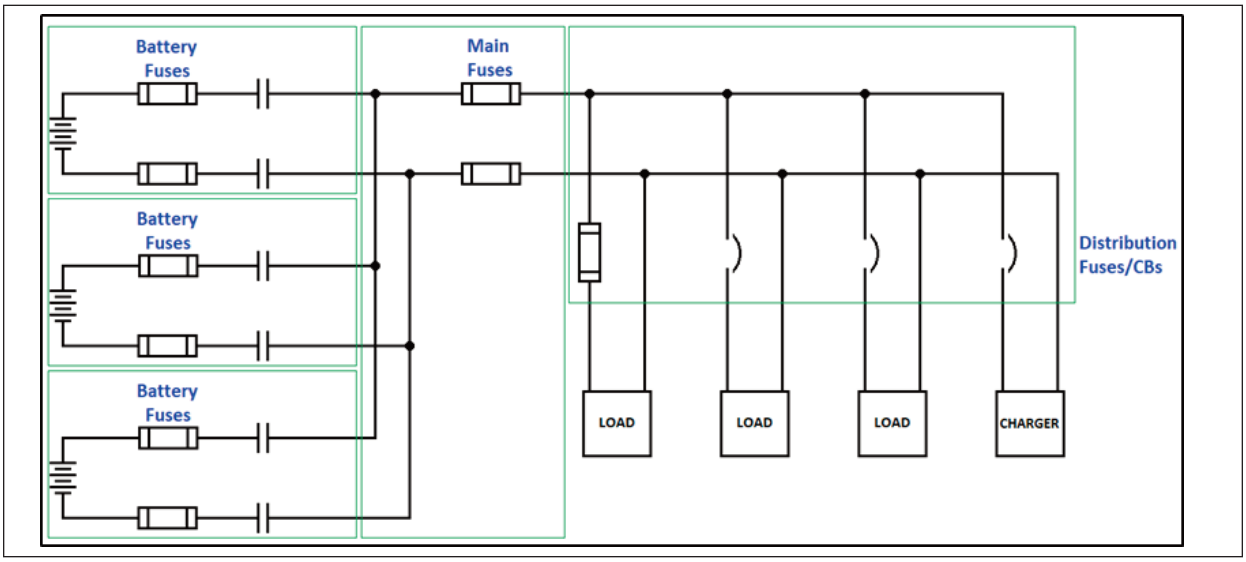


Figure 5.2. DC System Architecture

5.3.2 System Modelling, Fault Current, and Arc Flash

To help confirm that the HVDC system of the BEV is designed in accordance with electrical design principles, the distribution system should be modelled to understand its behaviour under both steady state and upset conditions.

It is essential to calculate the available short-circuit fault current for the system to determine the rating of the electrical components – in particular, the overcurrent protective devices such as fuses and circuit breakers. A mid-sized BEV battery system is often capable of delivering upward of 10 kA under bolted short-circuit conditions.

Battery pack voltage and internal resistance are key parameters that determine available fault current. These parameters vary according to the SOC. An equipment duty study can be used to make sure that all electrical components are able to withstand the full range of voltage and current to which they can be subjected.

While the electrical distribution scheme on-board a BEV is relatively simple, a protection coordination study should be undertaken to determine the sequence in which the overcurrent protective devices will operate under both short-circuit and overload conditions.

An arc flash study should be performed in order to estimate the incident energy that would be present in the event of an arcing fault. The arc flash study should be conducted in alignment with the workplace electrical safety standard applicable in the jurisdiction to which the BEV will be delivered. Examples of such standards include NFPA 70E and CSA Z462.

Arc flash calculation methods are based on experimental results from testing. While there is a wealth of arc flash test data for AC systems, the data for DC arc flash is quite limited, which is why there are a number of methods to calculate arc flash for DC systems. Some existing methods include Phillips (2016) *Complete Guide to Arc Flash Hazard Calculation Studies* and Doan (2010) "Arc Flash Calculations for Exposures to DC Systems." It should be noted that Doan's method has been shown to yield very conservative results, thus modelled incident energy will likely be in the order of 3-10 times higher than any actual arc flash scenario (Weimann, 2018). These results could result in maintenance personnel being required to wear PPE in excess of the hazard that can actually be present.

The outcome of an arc flash study is highly dependent on the battery system parameters such as voltage and internal resistance. These battery characteristics should be carefully validated and entered into the model. These parameters vary somewhat depending on the battery SOC, therefore it is recommended to perform arc flash calculations at various SOC values. It is not unusual for the greatest arc flash hazard to exist at the lowest battery SOC. Referencing the diagram from the battery manufacturer that provides open circuit voltage versus SOC values could be useful.

When the arc flash study is completed, a set of arc flash labels are affixed near the sources of the arc flash hazards. The requirements for an arc flash label vary by region, but NFPA 70E and CSA Z462 provide some examples.

5.3.3 Overcurrent and Overvoltage Protection

Overcurrent protection for energy storage systems is crucial for BEVs. If not properly interrupted, a short-circuit will result in the stored energy of the battery being released in the form of intense electrical arcing and uncontrolled heating of the battery system. In many situations, this can lead to injury, a battery fire, and irreparable damage to the BEV.

Energy storage systems, whether within or outside the BEV, should be protected against fault current and overcurrent. An overcurrent 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 overcurrent protective device should be rated to interrupt the maximum fault current available from a fully charged energy storage system.

Overvoltage should also be considered, and the high-voltage bus voltage should be controlled to protect high-voltage components from overvoltage consequences. The overvoltage protection should be independent of the battery contactors status.

5.3.4 Insulation/Ground Fault Monitoring

Because 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, UL 2231-1, and ISO 6469-3). 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 of the risk of electric shock due to a compromised high-voltage electrical system. These systems continuously monitor the path between the high-voltage electrical system and the vehicle chassis and alert personnel that there is a risk of electric shock from coming 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 can 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 is an example of a standard that includes such tests). 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.

5.3.5 Isolation and Service Disconnect

When performing an absence of voltage test of the high-voltage electrical system, it can be possible to reduce or potentially eliminate the requirement for arc flash PPE and setting physical boundaries. Even if absence of voltage can be reliably confirmed without exposing the technician to potentially energized high voltage components, this does not eliminate the necessity of an arc flash study as all risks need to be identified and then assessed.

An example of a remote validation method would be a voltage test station with a voltage presence indicator and terminals to measure the voltage within the system. These voltage test stations provide the technician the ability to confirm absence of voltage without exposing bare terminals or opening a panel which would otherwise protect from arc flash and electric shock. Voltage test stations should be used in conjunction with appropriate safe shutdown procedures and are not a replacement for a high-voltage lockout/tagout procedure.

5.3.6 Traction Drive and Motor

The electric motors that power BEVs are mostly three-phase AC motors. These motor technologies vary, and a key difference is the number of permanent magnets. Permanent magnets make the motors smaller but are also more costly due to the rare-earth metals in the magnets. The type of motor best suited for a BEV depends on the type, size, and cost of the vehicle. The motors are normally liquid cooled with water-glycol or oil.

There are two safety issues to consider in addition to electrical and mechanical safety issues present on all motors:

- Motors with permanent magnets produce voltage when forced to rotate, which can be a problem during towing.
- The strong permanent magnets can crush fingers during disassembly of such a motor. Although rare, these service incidents require special actions.

Traction motors are controlled by inverters that transform DC from the battery to AC with varying frequency to control the speed of the motor. The inverters have a variety of control settings and are vital parts of the drivetrain control systems, most of which are liquid cooled.

5.3.7 Auxiliary Drives and Motors

The technology in the motors for auxiliary drives is similar to traction motors in that they are also powered from inverters of the same type.

5.3.8 DC/DC Conversion

A BEV needs a 12 V or 24 V electric system to power components such as the control system and lights. That system is powered from the large battery through a DC/DC converter. A smaller 12/24 V battery is needed to power the control system during start-up of the large battery.

5.3.9 Battery Charger Integration

In many instances, 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 and bolters).

• Types of Charging and Connection Interfaces, Section 8

5.4 LOW VOLTAGE AND CONTROL SYSTEM

This section covers BEV design considerations about low voltage and control systems.

5.4.1 Low-Voltage Distribution and Control

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.

5.4.2 High-Voltage Interlock Loop (HVIL)

A high-voltage interlock loop (HVIL) should be used to prevent direct exposure of high voltage on BEVs (Figure 5.3 and Figure 5.4). It should be used for lids, covers, and connectors that do not fulfill ingress protection class IP2X code (IEC 60529) 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 can be supplemented with discharge function for high voltage to decrease discharge time. Additional circuits might be available as a risk mitigation against faulty high voltage connectors.

5.4.3 Master Disconnect

A BEV should incorporate one or more manual master disconnect devices (possible configuration illustrated in Figure 5.5), 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, however, it does have the capability to incorporate lockout/tagout.

5.4.4 Emergency Stop

If the hazards and risks associated with 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 or other applicable standard that deals with safety aspect(s) or one or more types of safeguard that can be used across a wide range of machinery.

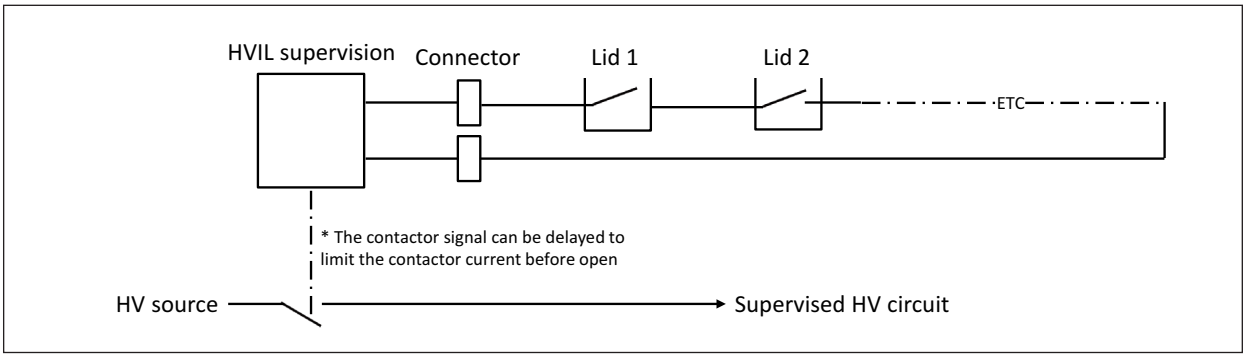


Figure 5.3. Conceptual Diagram of High-Voltage Interlock Loop (HVIL)

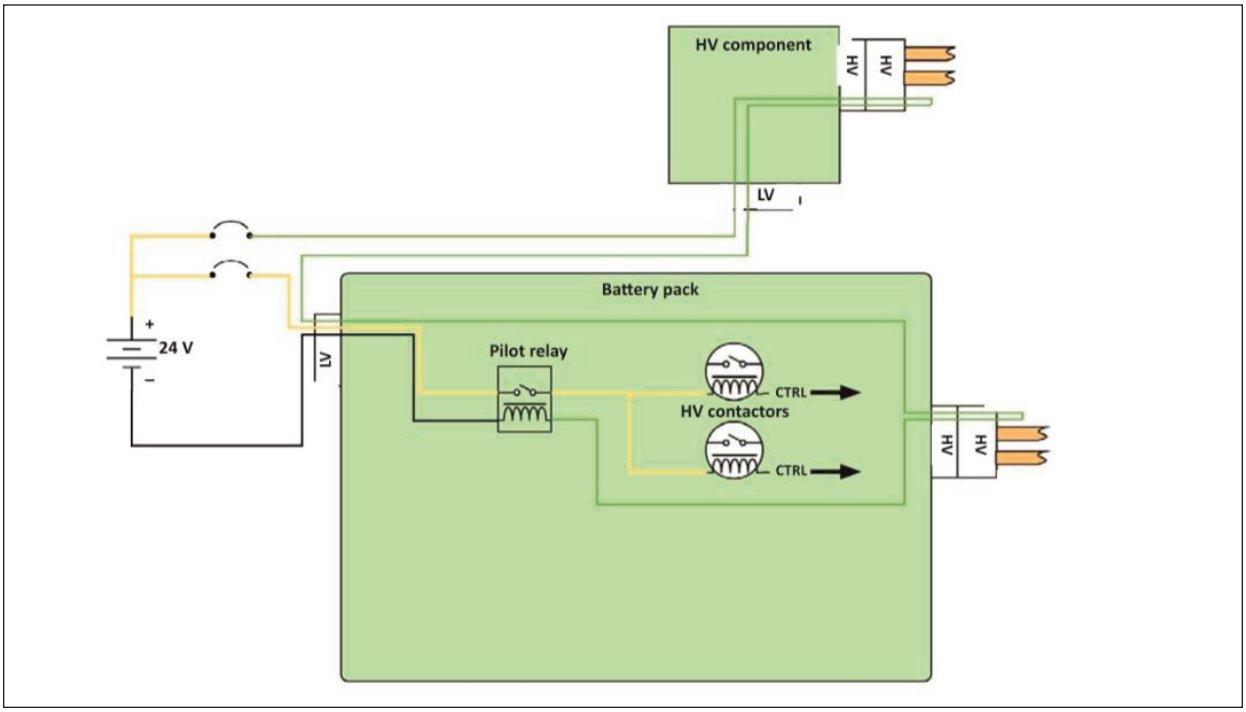


Figure 5.4. Example of High-Voltage Interlock Loop (HVIL)

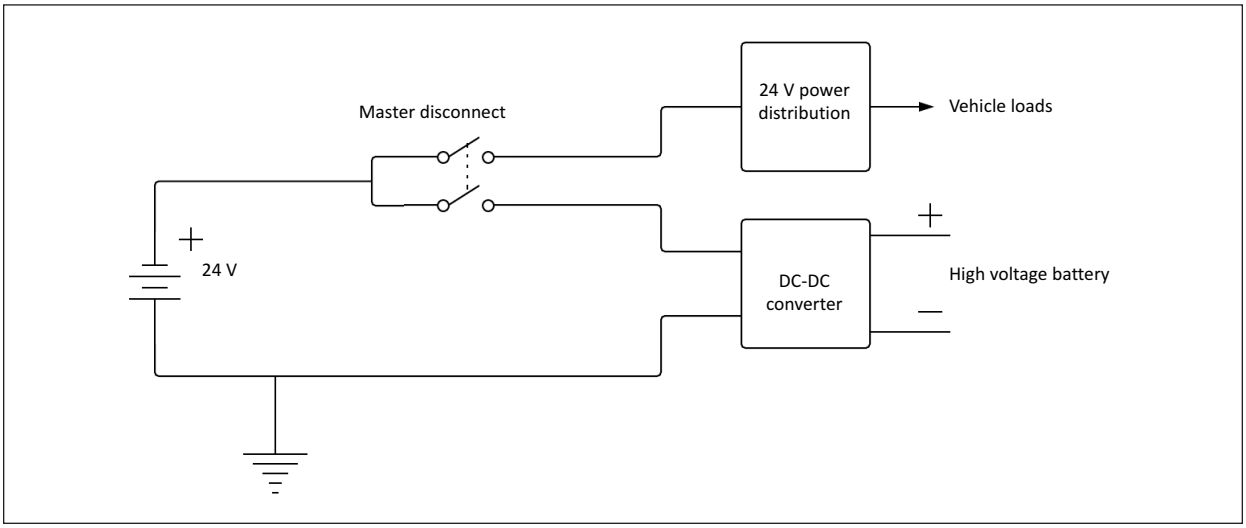


Figure 5.5. Example of a Master Disconnect Device

5.4.5 Operator Interfaces

The symbols for operator controls and displays should be designed in accordance with current versions of ISO 6405-1 and ISO 6405-2 or other applicable standards. The BEV operator interface is the site of human-machine interaction, so it is critical for a correct and safe BEV operation. In addition to the operator interface requirements by the machine, such as those prescribed in ISO 6011 or other applicable standards, the operator interface should visually display information about the battery SOC to the operator at all times since the SOC determines the power available to get the machine back to a charger.

- Battery Management System, Section 6.3.1
- Charging System Operations and Controls, Section 7.6

Visible and audible signals are also part of the operator interface, for example:

- A manual alarm to notify personnel that the BEV is underway. Some road vehicle standards on sound requirements such as FMVSS 141 are available, although not all aspects of such standards will be applicable to mining equipment.
- Automatic alarms to notify the operator that the SOC is at a critical level, the insulation resistance is low, or if battery cells have been automatically disabled due to malfunction.

The SOC is also 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 should be capable of alerting the operator. If the SOC or temperature prevents the battery from absorbing the regenerative energy, the operator should be warned if the vehicle's braking performance will be affected. This warning is particularly important if service brakes create only regenerative energy and their capacity is affected by the battery SOC. Alternatively, the regenerative braking functionality can be automatically turned off before the battery SOC limits brake capacity. The regenerative braking state (on or off) should always be clearly displayed on the operator interface.

5.4.6 Software/Firmware Risk Assessment

It is highly recommended that a risk assessment is completed whenever BEVs, charging systems, and other BEV support equipment are planned for a mine. The mine operator typically completes a risk assessment for the application of the equipment, but should consult with the OEM for information on the design risk assessment. 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.

- Risk Assessment, Section 4.10

Differences in design and applications of BEVs mean a detailed recommendation is not possible. It is recommended that during the risk assessment process, mine operations work closely with the OEMs to identify firmware/software-based functions that should be included in the risk analysis. Open protocols such as ethernet/industrial protocol (EtherNet/IP) should be considered when conducting a risk analysis. Additionally, 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.

5.4.7 Remote Control

Several factors should be considered when designing a system that can be controlled remotely. The following factors are unique to, or can be of significance to BEV design:

- Communicating SOC and warnings to a remote operator
- Whether or not charging infrastructure needs to be automated or remotely controlled

The list is not comprehensive: all the factors typically used in a diesel-powered application should also be considered. Some standards that cover remote operations include ISO 15817, ISO 17757, and AS/NZS 4240.1.

5.5 ELECTRICAL AND RADIO INTERFERENCE

To be sure that BEVs do not adversely affect nearby equipment, communication devices, or other microprocessor-controlled devices due to electrical and radio interference, they should be designed to conform to electromagnetic compatibility standards such as ISO 13766-1 and ISO 13766-2 or other applicable standards that outline requirements and limit values for electromagnetic emission and immunity to external electromagnetic fields, as well as the procedure and criteria for testing machinery and associated electrical/electronic systems.

The risk of interference with blasting caps is a key concern. During electric blasting, an employer and a blaster should make sure that minimum distances from radio frequency transmitters are maintained as detailed in SLP 20 or other applicable standards or guidelines. For example, the Institute of Makers of Explosives (2011) 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."

5.6 DRIVETRAIN

A BEV for underground mining normally has one central motor, two axle motors, or four wheel motors. More motors reduce the need for mechanical drivetrain but add cost and can add complexity. The best practices for motor setup for an underground BEV depend on the vehicle type and size.

Wheel or axle motors are connected to the wheels through fixed-gear reduction. A central motor is connected through a fixed reduction or a gearbox. The motor needs to be oversized in case it is fixed to get enough traction force and high vehicle speed, but it can be smaller if a gearbox is used. It is possible to use gearboxes with wheel or axle motors, however it is less common.

Hydraulic pumps and other pumps are mechanically driven from the engine in diesel-powered vehicles. In BEVs where the traction motor runs in both directions and sometimes stands still, a separate electric motor is needed to power the pumps. This allows control of the pump speed according to flow need instead of engine speed, which will reduce losses. More than one motor can be used to power pumps, further reducing losses but adding costs and potentially adding complexity. With a low-cost version, pumps can be connected to the traction motor where it spins with the gearbox in neutral while standing still. This can be suitable in small or low-cost vehicles for which energy efficiency is less important.

The cooling system on a BEV handles much less heat but runs at a lower temperature than cooling systems for diesel-powered vehicles. There are also a large number of components to cool, so the cooling system can be quite complex.

5.7 FIRE SAFETY

The fire suppression strategy for a BEV will be in alignment with local legislation and code, OEM documentation, and insurance policies. The system should be designed to help make sure that vehicle fire does not propagate to the battery.

Other sections of this guideline provide further information on fire safety.

- Battery and Fire Safety, Section 4.8
- Fire Hazards and Suppression, Section 6.4.4

5.8 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 19014-1, IEC 60068-2-64, or other applicable standard should be met. Standards used for passenger cars such as IEC 60068-2-6 and ISO 16750-3 can be applicable to personal carrier BEVs but might not be directly applicable to other mining BEVs.

5.9 MAINTENANCE AND SERVICE AREAS ON THE EQUIPMENT

- Design of Maintenance Areas (Mine Design), Section 4.3
- Operation and Maintenance of Charging Systems, Section 4.6.6
- Training, Section 4.9

High-voltage energy is always present in vehicle battery systems because components can 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 can require special procedures to bring down overall potential to an acceptable service value. OEMs should provide recommended schedules and procedures for inspecting and maintaining BEVs and their components. BEVs intended for use in mines should typically be ruggedly constructed and designed to facilitate inspection and maintenance by a skilled person.

Some maintenance considerations around BEV design include:

Components

- Arrangement of components 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
- High- and low-voltage components separated
- Battery electric systems with a VDC of 75 or higher; the main system voltage should be identified according to a relevant standard (e.g., ISO IEC 60204-1, see Table 5.1)

Enclosures and covers

- Access openings in enclosures located only where necessary for maintenance or inspection
- 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
- In the event that a high-voltage enclosure can be opened without tools, it should be touch-safe
- Enclosures where access is for maintenance personnel only; barriers, partitions, and covers provided and arranged so that testing and troubleshooting can be safely conducted
- Conductors energized with high voltages should be located behind protective covers that require a tool to access or remove

Service areas

- 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.
- Service areas accessed without tools containing high 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 high 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 low 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.
- Conductors energized with high voltages should be located behind protective covers that require a tool to access or remove.

Signage and labels

- Appropriate signage attached for service
- Warning labels should not be attached to removable protective covers
- Signage to discourage welding or other modifications to the battery and electrical system

5.10 STANDARDS CITED IN THIS SECTION

The following standards are cited throughout the section. The table is not intended to be comprehensive, and not all standards listed will be applicable to all situations. It is the responsibility of the user to reference local regulations and implement the appropriate standard for their situation. The citations listed are for the latest version of the standard at the time of this guideline's publication. Please consult the most recent version of any standard referenced.

Table 5.1. List of Standards Cited in the BEV Design Section (listed in the order they are cited)

Sections(s)	Standard	Topic	Jurisdiction	Citation
Section 5.1 Introduction Section 5.2 Braking System	ISO 13849-1 *Safety of machinery—Safety-related parts of control systems—Part 1: General principles for design*	Functional safety standard, not specific to BEVs. Safety requirements and guidance on design and integration of safety-related parts of control systems including software	International	International Organization for Standardization, 2015b
Section 5.1 Introduction Section 5.8 Shock and Vibration	ISO 19014-1 *Earth-moving machinery — Functional safety — Part 1: Methodology to determine safety-related parts of the control system and performance requirements*	Functional safety standard for earth-moving machinery, but not specific to BEVs. Provides methodology for determining performance levels	International	International Organization for Standardization, 2018c
Section 5.1 Introduction	IEC 61508-1 *Functional safety of electrical/electronic/ programmable electronic safety related systems – Part 1: General requirements*	Overall functional safety standard for electrical /electronic/programmable electronic safety-related systems, but not specific to BEVs	International	International Electrotechnical Commission, 2010
Section 5.2 Braking System	ISO 3450 *Earth moving machinery—Wheeled or high-speed rubber-tracked machines— Performance requirements and test procedures for brake systems*	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
Section 5.2 Braking System	CAN/CSA-M424.3-M90 *Braking performance—Rubber-tired, self-propelled underground mining machines*	Minimum performance criteria for the service braking, secondary braking, and parking system for rubber-tired, self-propelled underground mining machines	Canada	CSA Group, 2020
Section 5.2 Braking System	ISO 13849-2 *Safety of machinery—Safety-related parts of control systems—Part 2: Validation*	Functional safety standard. Procedures and conditions to validate by analysis and testing specified safety functions, the category achieved, the performance level achieved by the safety-related parts of a control system designed in accordance with ISO 13849-1	International	International Organization for Standardization, 2012c
Section 5.3 HVDC Electrical System	*ISO 14990-1 Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 1: General requirements*	General safety requirements for electrical equipment and components incorporated into earth-moving machines as defined in ISO 6165	International	International Organization for Standardization, 2016a
Section 5.3 HVDC Electrical System	*ISO 14990-2 Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 2: Particular requirements for externally-powered machines*	Safety requirements for electrical equipment and for components incorporated in externally-powered (mains–connected or dedicated generators), electrically-driven earth moving machines	International	International Organization for Standardization, 2016b
Section 5.3 HVDC Electrical System	ISO 14990-3 *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 3: Particular requirements for self-powered machines*	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

Table 5.1. List of Standards Cited in the BEV Design Section (listed in the order they are cited)

Sections(s)	Standard	Topic	Jurisdiction	Citation
Section 5.3.2 System Modelling, Fault Current, and Arc Flash	NFPA 70E *Standard for Electrical Safety in the Workplace*	Requirements to protect personnel by reducing exposure to electrical hazards	United States	National Fire Protection Association, 2021
Section 5.3.2 System Modelling, Fault Current, and Arc Flash	CSA Z462 *Workplace electrical safety*	Guidance on safety management systems, safe work procedures, PPE, and other safety devices to protect people from hazards associated with electrical equipment	Canada	CSA Group, 2021
Section 5.3.4 Insulation/ Ground Fault Monitoring	IEC 60204-1 *Safety of machinery—Electrical equipment of machines—Part 1: General requirements*	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
Section 5.3.4 Insulation/ Ground Fault Monitoring Section 5.9 Maintenance and Service Areas on the Equipment	UL 2231-1 *Standard for safety for personnel protection systems for electric vehicle (EV) supply circuits: General requirements*	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, 2012
Section 5.4.2 High-Voltage Interlock Loop (HVIL)	ISO 6469-3 *Electrically propelled road vehicles Safety specifications—Part 3: Protection of persons against electric shock*	Note that this is a road vehicle standard for reference only and not directly applicable to mining BEVs. 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, 2018d
Section 5.4.2 High-Voltage Interlock Loop (HVIL)	IEC 60529 Degrees of protection provided by enclosures (IP Code)	Specific to degrees of protection provided by enclosures for electric equipment (rated voltage not exceeding 72.5 kV)	International	International Electrotechnical Commission, 2013
Section 5.4.4 Emergency Stop	ISO 13850 Safety of machinery—Emergency stop function—Principles for design	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
Section 5.4.5 Operator Interfaces	1SO 6405–1 *Earth moving machinery—Symbols for operator controls and other displays—Part 1: Common symbols*	Standardizes symbols on operator controls and other displays on multiple types of earth-moving machines as defined in 1SO 6165	International	International Organization for Standardization, 2017a
Section 5.4.5 Operator Interfaces	1SO 6405–2 *Earth moving machinery—Symbols for operator controls and other displays—Part 2: Symbols for specific machines, equipment and accessories*	Standardizes symbols on operator controls and other displays on specific machines, equipment, and accessories as defined in 1SO 6165	International	International Organization for Standardization, 2017b
Section 5.4.5 Operator Interface	ISO 6011 *Earth-moving machinery — Visual display of machine operation*	Functional information presented on visual displays of earth-moving machinery	International	International Organization for Standardization, 2003
Section 5.4.5 Operator Interfaces	FMVSS 141 *Minimum sound requirements for hybrid and electric vehicles*	Note that this is a highway vehicle standard for reference only and not be directly applicable to mining BEVs. Minimum sound requirements for BEV's to warn persons that BEV is underway	USA	United States National Highway traffic safety administration, 2013

Table 5.1. List of Standards Cited in the BEV Design Section (listed in the order they are cited) (continued)

Sections(s)	Standard	Topic	Jurisdiction	Citation
Section 5.4.7 Remote Control	ISO 15817 *Earth-moving machinery—Safety requirements for remote operator control systems*	Example of a standard that covers remote operations. Safety requirements for remote operator control systems used on earth-moving machinery as defined in ISO 6165	International	International Organization for Standardization, 2012d
Section 5.4.7 Remote Control	ISO 17757 *Earth-moving machinery and mining Autonomous and semi-autonomous machine system safety*	Example of a standard that covers remote operations. Safety requirements for autonomous and semi- autonomous machines and systems used in earth-moving and mining operations	International	International Organization for Standardization, 2019a
Section 5.4.7 Remote Control	AS/NZS 4240.1 *Remote control systems for mining equipment Design, construction, testing, installation and commissioning*	Example of a standard that covers remote operations. 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
Section 5.5 Electrical and Radio Interference	ISO 13766-1 – *Earth-moving and building construction machinery—Electromagnetic compatibility (EMC) of machines with internal electrical power supply—Part 1: General EMC requirements under typical electromagnetic environmental conditions*	General EMC. Test methods and acceptance criteria for evaluating the EMC of earth moving machines as defined in ISO 6165	International	International Organization for Standardization 2018a
Section 5.5 Electrical and Radio Interference	ISO 13766-2 *Earth-moving and building construction machinery—Electromagnetic compatibility (EMC) of machines with internal electrical power supply—Part 2: Additional EMC requirements for functional safety*	General EMC standard. Safety-related parts of the control system. Test methods and acceptance criteria for evaluating the EMC of earth moving machines as defined in ISO 6165	International	International Organization for Standardization 2018b
Section 5.5 Electrical and Radio Interference	SLP 20 *Safety guide for the prevention of radio frequency radiation hazards in the use of commercial electric detonators (blasting caps*)	Suggest guidelines for the safe use of commercial electric detonators near radio frequency energy sources	USA	Institute of Makers of Explosives, 2011
Section 5.8 Shock and Vibration	IEC 60068-2-64*Environmental testing - Part 2-64: Tests - Test Fh: Vibration, broadband random and guidance* (Consolidated Version)	Tests to demonstrate the adequacy of specimens to resist dynamic loads without unacceptable degradation of its functional and/or structural integrity when subjected to the specified random vibration test requirement	International	International Electrotechnical Commission, 2019
Section 5.8 Shock and Vibration	IEC 60068-2–6 *Environmental testing—Part 2–6: Tests—Test Fc: Vibration (sinusoidal)*	Standard procedure to determine the ability of components, equipment, and other articles to withstand specified severities of sinusoidal vibration. Note that these tests are used for smaller vehicles and might not apply to heavy mining BEVs	International	International Electrotechnical Commission, 2007a
Section 5.8 Shock and Vibration	ISO 16750-3 *Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 3: Mechanical loads*	Applies to electric and electronic systems/components for road vehicles. As a road vehicle standard, it does not apply to heavy mining BEVs, but might be a relevant reference for personnel carriers	International	International Organization for Standardization, 2012b

SECTION REFERENCES

CSA Group. (2020a). *Braking performance—Rubber-tired, self-propelled underground mining machines* (Standard No. CAN/CSA-M424.3-M90 [R2020]). CSA Group. https://www.csagroup.org/store/product/CAN%25100CSA-M424.3-M90/

CSA Group. (2021). *Workplace electrical safety* (Standard No.Z462:21). CSA Group. https://www.csagroup.org/store/product/CSA%20Z462%3A21/

Doan, R. D. (2010). Arc Flash Calculations for Exposures to DC Systems. Vol. 46, no. 6, pp. 2299-2302. Doi: 10.1109/TIA.2010.2070480

Institute of Makers of Explosives. (2011). *Safety guide for the prevention of radio frequency radiation hazards in the use of commercial electric detonators (blasting caps)* (Standard No. SLP 20). https://www.ime.org/products/details/slp20

International Electrotechnical Commission. (2004). *International Electrotechnical Vocabulary Part 826: Electrical installations* (Standard No. IEC 60050-826:2004). https://webstore.iec.ch/publication/266

International Electrotechnical Commission (2007a). *Environmental testing—Part 2–6: Tests—Test Fc: Vibration (sinusoidal)* (Standard No. IEC 60068-2-6:2007). https://webstore.iec.ch/publication/544

International Electrotechnical Commission. (2010a). *Functional safety of electrical/electronic/programmable electronic safety related systems – Part 1: General requirements* (Standard No. IEC 61508-1:2010). https://webstore.iec.ch/publication/5515

International Electrotechnical Commission. (2013). *Degrees of protection provided by enclosures (IP Code)*. (Standard No. IEC 60529:1989+AMD1:1999+AMD2:2013 CSV). https://webstore.iec.ch/publication/2452

International Electrotechnical Commission. (2016b). *Safety of machinery—Electrical equipment of machines—Part 1: General requirements* (Standard No. IEC 60204-1:2016). https://webstore.iec.ch/publication/26037

International Organization for Standardization. (2003). *Earth-moving machinery — Visual display of machine operation* (Standard No. ISO 6011:2003). https://www.iso.org/standard/30309.html

International Organization for Standardization. (2011a). *Earth moving machinery— Wheeled or high-speed rubber-tracked machines— Performance requirements and test procedures for brake systems* (Standard No. ISO 3450:2011). https://www.iso.org/standard/42076.html

International Organization for Standardization. (2012a). *Earth moving machinery—Basic types—Identification and terms and definitions* (Standard No. ISO 6165:2012). https://www.iso.org/standard/52639.html

International Organization for Standardization. (2012b). *Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 3: Mechanical loads* (Standard No. ISO 16750-3:2012). https://www.iso.org/standard/58049.html

International Organization for Standardization. (2012c). *Safety of machinery—Safety-related parts of control systems—Part 2: Validation* (Standard No. ISO 13849-2:2012). https://www.iso.org/standard/53640.html

International Organization for Standardization. (2012d). *Earth-moving machinery—Safety requirements for remote operator control systems* (Standard No. ISO 15817:2012). https://www.iso.org/standard/46237.html

International Organization for Standardization. (2015a). *Safety of machinery—Emergency stop function—Principles for design* (Standard No. ISO 13850:2015). https://www.iso.org/standard/59970.html

International Organization for Standardization. (2015b). *Safety of machinery—Safety-related parts of control systems—Part 1: General principles for design* (Standard No. ISO 13849-1:2015). https://www.iso.org/standard/69883.html

International Organization for Standardization. (2016a). *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 1: General requirements* (Standard No. ISO 14990-1:2016). https://www.iso.org/standard/63299.html

International Organization for Standardization. (2016b). *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 2: Particular requirements for externally-powered machines* (Standard No. ISO 14990-2:2016). https://www.iso.org/standard/63301.html

International Organization for Standardization. (2016c). *Earth-moving machinery—Electrical safety of machines utilizing electric drives and related components and systems—Part 3: Particular requirements for self-powered machines* (Standard No. ISO 14990-3:2016). https://www.iso.org/standard/63302.html

International Organization for Standardization. (2017a). *Earth moving machinery—Symbols for operator controls and other displays—Part 1: Common symbols* (Standard No. ISO 6405-1:2017). https://www.iso.org/standard/68551.html

International Organization for Standardization (2017b). *Earth moving machinery—Symbols for operator controls and other displays—Part 2: Symbols for specific machines, equipment and accessories* (Standard No. ISO 6405-2:201). https://www.iso.org/standard/68552.html

International Organization for Standardization. (2018a). *Earth-moving and building construction machinery—Electromagnetic compatibility (EMC) of machines with internal electrical power supply—Part 1: General EMC requirements under typical electromagnetic environmental conditions* (Standard No. ISO 13766-1:2018). https://www.iso.org/standard/67347.html

International Organization for Standardization. (2018b). *Earth-moving and building construction machinery—Electromagnetic compatibility (EMC) of machines with internal electrical power supply—Part 2: Additional EMC requirements for functional safety* (Standard No. ISO 13766-2:2018). https://www.iso.org/standard/67403.html

International Organization for Standardization. (2018c). *Earth-moving machinery — Functional safety — Part 1: Methodology to determine safety-related parts of the control system and performance requirements* (Standard No. ISO 19014-1). https://www.iso.org/standard/70715.html

International Organization for Standardization. (2018d). *Electrically propelled road vehicles Safety specifications—Part 3: Protection of persons against electric shock* (Standard No. ISO 6469-3:2011). Retrieved from https://www.iso.org/standard/68667.html

International Organization for Standardization. (2019a). *Earth-moving machinery and mining Autonomous and semi-autonomous machine system safety* (Standard No. ISO 17757:2019). https://www.iso.org/standard/76126.html

Janiaud, N., Vallet, F.-X., Petit, M., & Sandou, G. (2009). Electric Vehicle Powertrain Architecture and Control Global Optimization. World Electric Vehicle Journal, 3(4), 682–693. https://doi.org/10.3390/wevj3040682

National Fire Protection Association. (2021). *Standard for Electrical Safety in the Workplace* (NFPA Standard No. NFPA 70E). https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70E

Phillips, J. (2016). *Complete Guide to Arc Flash Hazard Calculation Studies.* Brainfiller. https://brainfiller.com/product/complete-guide-to-arc-flash-hazard-calculation-studies/

IEEE. (2018). *IEEE Guide for Performing Arc Flash Hazard Calculations* (Standard No. 1584-2018). https://doi.org/10.1109/IEEESTD.2002.94138

Standards Australia. (2009). *Remote control systems for mining equipment Design, construction, testing, installation and commissioning* (Standard No. AS/NZS 4240.1:2009). https://infostore.saiglobal.com/en-us/standards/as-nzs-4240-1-2009-1114738/

UL (2012). *Standard for safety for personnel protection systems for electric vehicle (EV) supply circuits: General requirements* (Standard No. UL 2231-1). 2nd Ed. https://standardscatalog.ul.com/standards/en/standard_2231-1_2

United States National Highway Traffic Safety Administration (2013). *Minimum sound requirements for hybrid and electric vehicles* (FMVSS No. 141). https://www.federalregister.gov/documents/2013/01/14/2013-00359/federal-motor-vehicle-safety-standards-minimum-sound-requirements-for-hybrid-and-electric-vehicles

Weimann, S.C,. (2020). *Analytical and Experimental Validation for DC Arc Flash Models.* University of Pittsburgh. https://d-scholarship.pitt.edu/39317/1/Weimann-ETD-07162020.pdf

6. ENERGY STORAGE SYSTEMS (BATTERIES)

6.1 INTRODUCTION

The rechargeable battery is central to BEV operations. The battery storage capacity (energy density) limits the range that the BEV can travel or perform its task between charges, which is the main obstacle facing widespread commercial and mining BEV implementation. 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 because BEVs are large, heavy, and have high energy demands.

- Battery Performance (Performance Standards), Section 9.4

Throughout this section, several standards are referenced by standard number. Table 6.5 at the end of this section lists the standards in the order they first appear and provides further information, including the title, description, and a citation.

This section includes information about the components, use, and design of energy storage systems (batteries), summarized in the navigation below.

Background on Battery Types (Section 6.2) Outlines some of the components of batteries and some commonly used battery types.

⚠ No specific safety guidance.

Functional Requirements (Section 6.3) Describes some of the functional considerations associated with monitoring, maintaining, testing, and storing batteries.

⚠ Designing for safety and controls to prevent incidents underpins many of the functional considerations outlined in this section, such as accessibility and service for inspections and preventive maintenance, automatic shutdown, safe system enclosures, extreme temperature considerations, safe storage, and end-of-life disposal.

Safety Requirements (Section 6.4) Provides context and offers guidance on hazard condition monitoring, prevention, and mitigation.

⚠ Core safety section. Hazards considered include charging/discharging at low temperature, over/undervoltage, overloading, overtemperature, external/internal short-circuit, external heating, chemical reactions, and flammable/toxic gas release. Includes subsections with a particular focus on LIB chemistry and thermal runaway, fire hazards and suppression, and transportation.

6.2 BACKGROUND ON BATTERY TYPES

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/sulphuric acid solution. Lead-acid batteries have long been—and continue to be—used in conjunction with fossil fuels to power cars, boats, and other vehicles.

Table 6.1 identifies the specific energy of some rechargeable battery types. Given the relatively high energy density of LIBs, 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-

Table 6.1. Specific Energy of Some Rechargeable Battery Types (non-exhaustive) (Data from Battery University, 2019 and Cowie, 2015)

Type	Specific Energy (Wh/kg)
Lead-acid	30–50
Nickel cadmium	45–80
Nickel metal hydride	60–120
Lithium-ion (cobalt)	150–250
Lithium-ion (manganese)	100–150
Lithium-ion (phosphate)	90–120
Lithium-titanate	30–110

cobalt-aluminum, or nickel-manganese-cobalt), manganese spinel, or iron phosphate (Canis, 2013). The cathode is separated from the graphite, carbon, or titanate anode by a porous polyethylene or polypropylene membrane (Figure 6.1). 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, which is kept at a temperature high enough for it to be liquid. The possibility of using ultracapacitaors (i.e., very high-capacity electrical capacitors) has been proposed, either on their own or in combination with batteries.

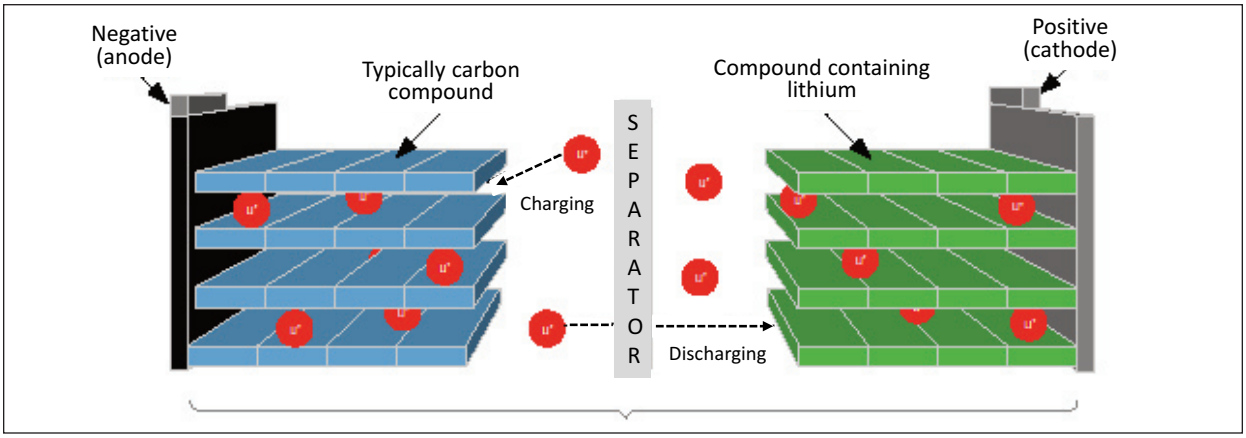


Figure 6.1. Conceptual Sketch of Lithium-Ion Battery

6.3 FUNCTIONAL REQUIREMENTS

This subsection describes some of the functional considerations associated with monitoring, maintaining, testing, and storing batteries.

6.3.1 Battery Management System

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, battery pack voltage, current, SOC, depth of discharge (DOD), temperature, and voltage of individual cells. The BMS also varies the current being delivered to the battery during charging. Additionally, the BMS redirects the energy produced during regenerative braking to the battery pack.

The BMS monitors large quantities of data related to the operation, performance, and health of the battery, and it should therefore be integrated into the BEV design and be able to communicate with charging infrastructure and emergency shutdown subsystems. 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.

6.3.2 Accessibility, Maintenance, and Service

Only a skilled person should perform maintenance and service on batteries. The OEM should provide a preventive maintenance program, including a checklist for inspection of the battery system and any special repair procedures. Making sure there are no live contacts on the terminal is a key consideration.

- Operator Interfaces (BEV Design), Section 5.4.6
- Maintenance and Service Areas (BEV Design), Section 5.9
- Safety Requirements (Energy Storage Systems), Section 6.4
- LIB Chemistry and Thermal Runaway, Section 6.4.4

6.3.3 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 is typically 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 short-circuiting 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, elevated temperatures accelerate the degradation of capacity and power in LIBs and can cause charge imbalance among battery cells.

Active testing of LIB overtemperature functionality should follow E/ECE/324/Rev.1/Add.82/Rev.5 or other applicable standards or regulations for the thermal shock and cycling test, and the overtemperature protection test. The ST/SG/AC.10/11/Rev.7 T.2 thermal test is similar to the thermal shock test within E/ECE/324/Rev.1/Add.82/Rev.5: the batteries are stored at 72°C for 6 hours and then at –40°C for 6 hours for 10 cycles. They should exhibit no leaking, venting, disassembly, rupture, or fire, and voltage cannot fall to less than 90% of the original voltage.

6.3.4 Cycle Performance and Battery Life

Battery system cycle performance is a key metric of battery life. Standard test procedures in SAE J2288 or another applicable standard 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. Specific testing (e.g., DOD, SOC, operating temperature) can be performed to better understand battery life under specific conditions.

• Battery Performance. Section 9.4

Certain battery types are better suited to unique underground usage profiles that are not captured in SAE J2288. These conditions and usage profiles should be defined and additional testing procedures can be applied to the systems to better estimate battery system life. The following standards are relevant references on aspects of the design and testing of battery systems, though other standards might also be applicable: E/ECE/324/Rev.1/Add.82/Rev.5, UL 1642, UL 2580, IEC 62133-2, IEC 62485-6, and IEC 62619.

6.3.5 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 overcharge and overdischarge 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 allowable operating parameters are exceeded. The automatic shutdown of the system should be designed and tested to based on relevant safety standards (e.g., IEC 61508, IEC 62061, and IEC 61010) where applicable. Information on BMS safety design and testing can also be found in Section 8 of IEC 62619.

6.3.6 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 (i.e., so that only qualified personnel can open the enclosure for activities such as maintenance or repair). Other battery system enclosure considerations include:

- Venting requirements based on energy storage chemistry
- Temperature monitoring
- Harsh 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

6.3.7 Extreme Temperature Considerations

Batteries have an optimal temperature range in which they perform most efficiently. This range is affected by the way the battery is designed and the battery chemistry. Operating a BEV outside that optimal battery temperature range means the battery does not perform to its full potential. In practice, these limitations can mean reducing the range

and/or requiring larger capacity batteries to offset the need for additional systems to raise or lower temperatures to the appropriate levels.

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 also on the passenger compartment heating and window defrosting systems.

Conversely, cooling the battery can be a challenge in extreme heat conditions. The upper limit might 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) might be needed.

6.3.8 Storage

The maximum number of batteries stored and the storage procedures in a particular location should be confirmed with the local authority. Protection and isolation during storage should follow CSA M421-16 or other applicable standard. The battery manufacturer or OEM should fully define the storage conditions for battery packs or components of interest, such as any devices containing battery cells that can be damaged or become inoperable by the effects of long-term storage. These storage conditions include but are not limited to:

- Storage temperature range and ideal storage temperature
- Component life with and without periodic SOC/state of health check
- Maintenance intervals and documented procedures
- 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 they are 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 instructions 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.

6.3.9 End-of-Life

Energy storage systems in BEVs have a limited life and will eventually wear out. End-of-life options for the battery system or individual replaceable components of the system should be fully defined by the OEM. When a BEV energy storage system reaches end-of-life, it should be properly decommissioned and disposed of in accordance with local laws. In some situations, the battery might need to be rebuilt by a qualified person (e.g., OEM, battery manufacturer, or qualified rebuild shop) to bring it back to compliance with specifications. Regardless of the approach taken, the battery system will need to be packaged and labelled according to its requirements before it is transported. These requirements vary by geographic location.

• Transportation (Safety Requirements), Section 6.4.5

While not universal, many transportation regulations require use of packaging designed and tested to the United Nations ST/SG/AC.10/Rev.21 content on lithium metal batteries and LIBs. Whereas disposal of used battery systems might 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 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. Reuse of energy storage systems at mine sites to store wind and solar energy is

another potential application. Similar to recycling of LIBs, the market for these second life applications has not yet fully matured. LIB systems have become more prevalent in propulsion systems; therefore, a significant increase in the quantity of battery systems 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 can 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 or battery manufacturer for instructions. Disposal, recycling, and transportation methods at the battery system end-of-life should always be made in consultation with the battery manufacturer and local laws. Components containing hazardous materials should be properly labelled to avoid improper disposal. OEMs should label energy storage systems to alert owners of the need for special packaging, transport, and disposal procedures. The energy storage system labelling should also include OEM contact information.

6.4 SAFETY REQUIREMENTS

This subsection provides context on hazard conditions and offers guidance on hazard condition monitoring, prevention, and mitigation.

6.4.1 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, and storage:

- Charging or discharging at low temperature
- Overvoltage (overcharge)
- Undervoltage (overdischarge)
- Overloading (overcurrent)
- Overtemperature
- External short-circuit
- Internal short-circuit
- External heating
- Chemical reactions
- Mechanical crush, shock, penetration, or rupture of a cell resulting in liquid or flammable/toxic gas release

The likelihood of the above hazards depends on the battery chemistry and how the design mitigates and addresses the risks. Safety data sheets for the BEV battery system should be made available by the battery manufacturer or OEM.

Table 6.2 provides further detail on some hazards and their causes, and comments on the possible effects. A number of these hazards can be mitigated with the implementation of a BMS.

The cumulative effects of electrical and chemical hazard conditions can lead to thermal runaway. Potential effects of these hazard conditions are gas release, heat release, fire, and corrosive electrolyte release. These hazards are strongly linked to thermal runaway and elevated levels of combustible and toxic gases.

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. Methods to prevent a cascading thermal runaway throughout the battery should be considered.

Another safety issue is cold temperature charging. Although some LIB packs appear to be charging normally, some cannot charge below 0°C. Permanent, irreversible plating of metallic lithium occurs on the anode during sub-freezing charging. If done repeatedly, cold temperature charging can compromise the safety of the pack, making the battery more vulnerable to failure if subjected to impact, crushing, or high-rate charging.

Table 6.2. Hazards and Causes for LIBs (see also Mikolajczak, Kahn, White, & Long, 2011).

Hazard	Cause	Effects
Thermal runaway	Overcharge, overvoltage	Can cause lithium plating, where lithium ions deposit dendritic metallic lithium on the anode, leading to a potential short-circuit.
	Overtemperature (70°C)	Can also lead to increased temperatures.
	Overdischarge, undervoltage	Can cause degradation of the solid electrolyte interphase (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 titanite anodes, which do not depend on the SEI layer.
	Overcurrent, rapid charge, and discharge	Can cause anode copper to dissolve in the electrolyte, which may form dendritic metallic copper when the cells voltage is increased, leading to potential short-circuit.
	Internal short-circuit due to cell defect	High currents can increase the temperature of the cells. See over-temperature.
	Internal short-circuit due to lithium plating, precipitated anode copper.	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 caused by overcharge or overdischarge.
	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. See over-temperature.
Venting	External heat source, fire, thermal runaway	Breakdown of organic solvents in the electrolyte into highly toxic and flammable gases.
Combustion of battery cells	Thermal runaway	Can occur when the flammable gases are released and mix with oxygen if the temperature is high enough or if there is an external source of heat or spark.
Rapid disassembly of battery module	Thermal runaway, poor venting	Battery modules could 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.

6.4.2 Hazard Condition Monitoring, Prevention, and Mitigation

Temperature detection by the BMS should be adequate to identify dangerous temperatures in the battery pack by having a sufficient number of temperature sensors next to battery cells. Sensor data are used to prevent the following hazard conditions by notifying the BEV control unit to take corrective action and cause an alarm if battery temperature is out of a safe operating range:

- Charging or discharging at low temperature
- Overvoltage (overcharge)
- Undervoltage (overdischarge)
- Overloading (overcurrent)
- Overtemperature

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.

External short-circuit conditions can be prevented by fusing. The following hazard conditions can be prevented by appropriate battery mechanical protection, usage, and handling:

- External heating

- Chemical reactions
- Mechanical crush, shock, penetration, or rupture of a cell resulting in liquid or flammable/toxic gas release

If electric, electronic, or software controls and systems are relied upon for critical safety, then the system should be subjected to analysis for functional safety. Based on the risk assessment, an integrity level or performance level target is acquired for the functions, and the BMS and other systems should be designed according to applicable standards.

During battery swap-out, a combination of intrinsically safe connections (touch-safe, fail-safe, and redundant systems) and procedures need to maintain 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 (as defined in International Electrotechnical Commission, 2004) should make sure that there is 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.

6.4.3 LIB Chemistry and Thermal Runaway

LIB thermal runaway occurs when the battery is heated to a critical temperature where self-heating enters into a positive feedback loop and temperature and outgassing increase exponentially. Thermal runaway can lead to excessive temperatures, rapid outgassing, flaming, or explosion of the battery itself. Flammable gases released before or during thermal runaway can mix with atmospheric oxygen to produce flammable gas-air mixtures that can be ignited by a competent ignition source.

Thermal runaway severity and susceptibility varies with LIB chemistry and battery design. Thermal runaway severity increases with self-heating temperature and heat of reaction. Table 6.3 lists thermal runaway maximum temperatures and heats of reaction for several 18650 form factor lithium-ion chemistries (Lei et al 2017, Hartmann 2020). The amount of heat needed to induce thermal failure in a lithium-ion battery provides a measure of thermal runaway susceptibility. Batteries that require more external heating to induce failure are less susceptible to thermal runaway. In one study, Tang et al (2020) measured the heat to failure for LFP, NMC and LTO LIB batteries, and found that the normalized total heat to failure by its energy capacity had the following ranking: LTO 18650 ≈ LFP 26650 ≈ LFP 18650 > NMC 18650. Note that the sources above are intended only for informational purposes. Susceptibility to heat and the risk of thermal runaway are the subject of various studies and no established consensus has been reached on the topic.

Table 6.3. Thermal Runaway Maximum Temperatures and Heats of Reaction for Several 18650 Form Factor Lithium-ion Chemistries (Lei et al 2017, Hartmann, 2020)

Chemistry	Tmax (°C)	Heat of reaction (kJ)
LFP	259	7.3
LMO	303	7.8
NMC	665-731	14.9-24.9
LCO	654-709	17.9-20.6
NCA	624	31.1

- Battery and Fire Safety (Mine Design), Section 4.8
- Explosion Protection for Gassy Mines, Appendix B

6.4.4 Fire Hazards and Suppression

The following subsections provide further detail on fire and explosion hazards associated with batteries and suppression and response in the event of a fire.

6.4.4.1 Fire And Explosion Hazards

LIBs can pose significant fire and explosion hazards when they are compromised, due to either physical damage or hazard conditions. Examples of abusive conditions include high temperature, overcharge, overdischarge, and external/internal short-circuit. When the battery is exposed to hazardous conditions, the temperature can exceed the normal operating range, and the active component materials will decompose or react with each

other, leading to thermal runaway. In theory, thermal runaway occurs when the heat generated by exothermic reactions inside the battery is not offset by the heat losses to the environment. The accumulated heat drives the temperature increase, which produces an exponential increase in the reaction rates. During the thermal runaway, an explosion can occur because the lithium-ion cell contains its own oxidizer.

Various quantities of gases can be released from the battery thermal runaway. These gases are usually high temperature, combustible, and toxic (Jones, et al., 2021), and the reignition of combustible gases results in a fire with the injection of flame or explosion under favourable conditions. For a battery pack consisting of hundreds of cells, the fire hazard can be much greater when many cells are undergoing thermal runaway in a short period. In addition, different chemistries used in such batteries can produce unusual toxic environments when fires or explosions of such batteries occur.

The heat release rate (HRR) is a key parameter to characterize a fire on the cell level. The HRR of a LIB cell depends on the battery mass, energy capacity, chemistry, and SOC. For a battery module, the HRR also depends on the number of cells and battery pack construction. A cylindrical 18650 battery with an energy capacity of 10 Wh and a mass of 44.3 g produces a peak HRR of 5.6 kW, while a pouch cell with an energy capacity of 11 Wh and a mass of 95 g produces a peak HRR of 20.9 kW (Sun et al., 2020). Yuan et al. (2020) found that for LFP, NMC, and LTO, the onset temperature for thermal runaway was 200, 145, and 163°C, respectively. The peak cell temperature for LFP, NMC, and LTO during thermal runaway was 399, 835, and 305°C, respectively, while the normalized gas volume released after thermal runaway was 36.5, 215.2, and 82.9 L/kg, respectively.

The flammable gases produced from battery thermal runaway include hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and other hydrogen carbon (hydrocarbon) gases. For the three battery chemistries, the H_2 concentration ranged from 8.41 to 24.34%, and CH_4 concentration ranged from 1.23 to 12.90% (Yuan et al., 2020).
The toxic gases produced during battery thermal runaway are mainly carbon monoxide (CO) and hydrogen fluoride (HF).

• Refuge Station Considerations (Mine Design), Section 4.8.1

Underground fires are especially dangerous because of the creation of CO. The fumes can spread quickly throughout the mine and without warning as it is an odourless, tasteless gas. The majority of fatalities caused by a fire or explosion are from CO poisoning. Concentrations of 1,600 parts per million (ppm) CO can be lethal within an hour while concentrations of 6,400 ppm can be lethal to a person in approximately one to three minutes. Yuan et al. (2020) measured CO concentrations ranging from 4.5 to 30.3% for NMC, LTO, and LFP cells, with NMC producing the highest and LFP producing the lowest. Those toxic gases can be transferred by ventilation airflow to active working sections, posing a threat to underground mine personnel. Based on the information of the toxic gases, the appropriate PPE can be selected for fire fighters and first responders.

LIB fires release a significant amount of HF when they burn, and HF has immediately dangerous to life or health (IDLH) 30 minute concentration of 30 ppm (CDC, 1994). Previous fire simulations indicate HF exceeds IDLH values quicker and earlier than CO. The emission rate of HF could range between 20 and 200 mg/Wh of nominal energy capacity (Larsson et al., 2017).

NMC, LFP, and LTO battery thermal runaways emit abundant aerosols in the respirable size range (Barone et al., 2021). Cobalt and other transition metals were observed in NMC and LTO samples but not in an LFP sample.

6.4.4.2 Fire Suppression and Response

Early detection of a battery fire and an effective fire responsive practice can prevent incidents from becoming more serious. LIB fires are known to have reignition behaviour, so suppression practices should consider containment and cooling. It is recommended to use a fire suppression agent that can act to contain and cool the battery fire. Dry chemical powder is a commonly used fire suppression agent in the mining environment. However, dry chemical powder does not constitute a sufficient suppressant for lithium-ion battery fires, as it lacks a cooling effect (Xu et al., 2020).

• Emergency Response and Battery Fires (Operations), Section 4.8.2

There have been several studies on the most effective battery fire suppression methods, some described below for context, but note that specific fire suppression and response methods should be determined in conjunction with local

regulations and recommendations. Water has been tested as a battery fire suppressant that can be effective under some conditions because it can both contain and cool the battery fire. Additionally, some research has found that water pressure and flow can enhance the effectiveness of fire suppression (Xu et al. 2020, Zhang et al. 2021). After the battery fire visibly disappears, it is recommended to continue applying water for cooling, as the chemical reactions inside the battery can fuel another fire. Similar to water, aqueous film-forming foams can be an effective fire suppressant for battery fire too with their excellent cooling effects (Russoa, et al., 2018). Some additives such as potassium bicarbonate ($KHCO_3$) can help cool down the battery more quickly (Liu et al., 2020). A handheld fire extinguisher unit with an F-500 encapsulator agent as an additive was sufficient to extinguish an 1890 Wh battery pack fire based on tests conducted by Kiwa Nederland BV (2017).

6.4.5 Transportation

Packaging, labelling, and notification precautions should be taken when transporting batteries for use or at end-of-life. Applicable regulations depend on the geographical region(s) where 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. The OEM should also be consulted. Transportation regulations such as those listed in Table 6.4 should be consulted before transporting batteries, battery systems, and BEVs and spare parts containing batteries.

• End-of-Life, Section 6.3.9

Damaged or suspect batteries should be transported according to applicable regulations. Local regulations—including those listed in Table 6.4—might 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.

Table 6.4. Dangerous Goods Transportation Regulations (non-exhaustive)

Regulation	Jurisdiction	Citation (refer to the latest version)
Canada TDG *Transportation of dangerous goods regulations*	Canada	Transport Canada, 2020
International Maritime Dangerous Goods (IMDG) Code 2020 (in force January 2022) and IMDG 2018 (in force January 2020)	International	International Maritime Organization, 2020
International Air Transport Association (IATA) Dangerous Goods Regulations	International	International Air Transport Association, 2021
ST/SG/AC.10/Rev.21 *Recommendations on the transport of dangerous goods: Model regulations, Volume 1*	International	United Nations, 2019b
ST/SG/AC.10/11/Rev.7 *Recommendations on the transport of dangerous goods: Manual of tests and criteria*	International	United Nations, 2019a
United States Code of Federal Regulations on Transportation Title 49, Parts 100 to 177	USA	United States Office of the Federal Register, 2012

6.5 STANDARDS CITED IN THIS SECTION

The following standards are cited throughout the section. The table is not intended to be comprehensive, and not all standards listed will be applicable to all situations. It is the responsibility of the user to reference local regulations and implement the appropriate standard for their situation. The citations listed are for the latest version of the standard at the time of this guideline's publication. Please consult the most recent version of any standard referenced.

Table 6.5. List of Standards Cited in the Energy Storage Systems Section (listed in the order they are cited)

Section	Industry Standard	Topic	Jurisdiction	Citation
Section 6.3.3 Thermal Management and Testing Section 6.3.4 Cycle Performance and Battery Life	E/ECE/324/Rev.1/Add.82/Rev.5 *Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train*	Safety requirements of vehicle electric power train	International	United Nations, 2015
Section 6.3.3 Thermal Management and Testing Section 6.4.5 Transportation	ST/SG/AC.10/11/Rev.7 *Recommendations on the transport of dangerous goods: Manual of tests and criteria*	Criteria, test methods, and procedures for classifying dangerous goods	International	United Nations, 2019a
Section 6.3.4 Cycle Performance and Battery Life	SAE J2288 *Lifecycle testing of electric vehicle battery modules*	Standardized test method to determine the expected life cycles of BEV battery modules	International	SAE International, 2020
Section 6.3.4 Cycle Performance and Battery Life	UL 1642 *Standard for lithium batteries*	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, 2020b
Section 6.3.4 Cycle Performance and Battery Life	UL 2580 *Batteries for use in electric vehicles*	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, 2020a
Section 6.3.4 Cycle Performance and Battery Life	IEC 62133-2 *Secondary cells and batteries containing alkaline or other non-acid electrolytes—Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications—Part 2: Lithium systems*	Requirements and tests for safe operation of portable sealed rechargeable lithium cells and LIBs containing non-acid electrolyte	International	International Electrotechnical Commission, 2021c
Section 6.3.4 Cycle Performance and Battery Life	IEC 62485-6 *Safety requirements for secondary batteries and battery installations - Part 6: Safe operation of lithium-ion batteries in traction applications*	Safe operation of LIBs in traction applications, applies to battery installations used for electric off-road vehicles	International	International Electrotechnical Commission, 2021b
Section 6.3.4 Cycle Performance and Battery Life Section 6.3.5 Automatic Shutdown	IEC 62619 *Secondary cells and batteries containing alkaline or other non-acid electrolytes–Safety requirements for secondary lithium cells and batteries, for use in industrial applications*	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries for use in industrial applications	International	International Electrotechnical Commission, 2017a
Section 6.3.5 Automatic Shutdown	IEC 61508 *Functional safety of electrical/electronic/programmable electronic safety-related systems—Parts 1 to 7 together with a commented version*	Aspects to be considered when electrical/electronic/programmable electronic systems are used to carry out safety functions	International	International Electrotechnical Commission, 2010

Table 6.5. List of Standards Cited in the Energy Storage Systems Section (listed in the order they are cited) (continued)

Section	Industry Standard	Topic	Jurisdiction	Citation
Section 6.3.5 Automatic Shutdown	IEC 62061 *Safety of machinery—Functional safety of safety-related electrical, electronic and programmable electronic control systems*	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, 2021a
Section 6.3.5 Automatic Shutdown	IEC 61010 *Safety requirements for electrical equipment for measurement, control, and laboratory use–Part 1: General requirements*	Safety requirements for electrical equipment for measurement, control and laboratory use – Part 1: General requirements	International	International Electrotechnical Commission, 2017b
Section 6.3.8 Storage Section 6.4.5 Transportation	CSA M421-16 *Use of electricity in mines*	Minimum requirements for electrical work and electrical equipment operating/intended to operate at a mine	Canada	CSA Group, 2016

SECTION REFERENCES

Barone, T., Dubaniewicz, T., Friend, S., Zlochower Z., Bugarski A., Rayyan N. (2021). *Lithium-ion battery explosion aerosols: Morphology and elemental composition.* Aerosol Science and Technology, 55(10), 1183-1201, https://doi.org/10.1080/02786826.2021.1938966

Battery University (2019). *BU-107: Comparison Table of Secondary Batteries*. https://batteryuniversity.com/article/bu-107-comparison-table-of-secondary-batteries_

Canis, B. (2013). *Battery manufacturing for hybrid and electric vehicles: Policy issues.* Congressional Research Service Report for Congress 7-5700 R41709. https://www.everycrsreport.com/reports/R41709.html

Cowie, Ivan (2015). *All About Batteries, Part 12: Lithium Titanate (LTO).* EE Times. https://www.eetimes.com/all-about-batteries-part-12-lithium-titanate-lto/

CSA Group. (2016). *Use of electricity in mines* (Standard No. M421-16[R2016]). CSA Group. https://www.csagroup.org/store/product/M421-16/

Hartmann, Mark. (2020). *Temperature Adjustable Thermal Management System with Thermal Runaway Protection for Li-ion Packs*. https://www.nasa.gov/sites/default/files/atoms/files/temp_adjust_therm_mgmnt_sys_therm_runaway_prot_mhartmann.pdf

International Air Transport Association (2021). *IATA Dangerous Goods Regulations.* https://www.iata.org/publications/dgr/Pages/index.aspx

International Electrotechnical Commission (2004). *International Electrotechnical Vocabulary Part 826: Electrical installations* (Standard No. IEC 60050-826:2004). https://webstore.iec.ch/publication/266

International Electrotechnical Commission (2010). *Functional safety of electrical/electronic/programmable electronic safety-related systems—Parts 1 to 7 together with a commented version* (Standard No. IEC 61508:2010). https://webstore.iec.ch/publication/5515

International Electrotechnical Commission (2017a) *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications* (Standard No. IEC 62619:2017). https://webstore.iec.ch/publication/28895

International Electrotechnical Commission (2017b) *Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 1: General requirements* (Standard No. IEC 61010-1:2010+AMD1:2016 CSV). https://webstore.iec.ch/publication/59769

International Electrotechnical Commission (2021a). *Safety of machinery—Functional safety of safety-related electrical, electronic and programmable electronic control systems* (Standard No. IEC 62061:2021). https://webstore.iec.ch/publication/59927

International Electrotechnical Commission (2021b). *Safety requirements for secondary batteries and battery installations - Part 6: Safe operation of lithium-ion batteries in traction applications* (Standard No. IEC 62485-6:2021). https://webstore.iec.ch/publication/32955

International Electrotechnical Commission (2021c). Secondary cells and batteries containing alkaline or other non-acid electrolytes—Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications—Part 2: Lithium systems (Standard No. IEC 62133-2:2017+AMD1:2021 CSV). https://webstore.iec.ch/publication/70017

International Maritime Organization (2020). *IMDG Code.* https://www.imo.org/en/publications/Pages/IMDG%20Code.aspx

Jones, K., Bhattacharya, S., & Surampudi, B (2021). *Safety Enhancing Technologies for Usage of Mulit-Cell Battery Power Sysetms in Underground Equipment.* SwRI Project No. 03.24852 prepared for the Centres for Diesease Control and Prevention.

Larsson, F., Andersson, P., Blomqvist, P. et al. (2017). *Toxic fluoride gas emissions from lithium-ion battery fires.* Scientific reports 7, 10018. https://doi.org/10.1038/s41598-017-09784-z

Lei, B., Zhao, W., Ziebert, C., Uhlmann, N., Rohde, M., & Seifert, H. (2017). *Experimental Analysis of Thermal Runaway in 18650 Cylindrical Li-Ion Cells Using an Accelerating Rate Calorimeter.* Batteries, 3(4), 14. https://doi.org/10.3390/batteries3020014

Liu Y., Duan Q., Xu J., Li H., Sun J., Wang Q. (2020). *Experimental study on a novel safety strategy of lithium ion battery integrating fire suppression and rapid cooling.* Journal of energy storage, 28, 101185. http://dx.doi.org/10.1016/j.est.2019.101185

Mikolajczak, C., Kahn, M., White, K., & Long, R. T. (2011). *Lithium-ion batteries hazard and use assessment—Phase I. Quincy, MA: The Fire Protection Research Foundation.* https://www.nfpa.org/News-and-Research/Data-research-and-tools/Hazardous-Materials/Lithium-ion-batteries-hazard-and-use-assessment

The National Institute for Occupational Safety and Health (1994). *Immediately Dangerous to Life or Health Concentrations (IDLH).* Centres for Disease Control and Prevention. https://www.cdc.gov/niosh/idlh/7664393.html

Russoa P., Di Bari C., Mazzaro M., De Rosa A., Morriello I. (2018). *Effective fire extinguishing systems for lithium-ion battery.* Chemical Engineering Transactions, 67, 727-732. http://dx.doi.org/10.3303%2FCET1867122

SAE International. (2020). *Lifecycle testing of electric vehicle battery modules* (Standard No. J2288_202011). https://www.sae.org/standards/content/j2288_202011/

Sun P., Bisschop R., Niu H., Huang X. (2020). *A review of battery fires in electric vehicles.* Fire Technology, 56, 1361-1410. https://doi.org/10.1007/s10694-019-00944-3

Tang W, Tam WC, Yuan L, Dubaniewicz TH, Thomas R, Soles J. (2020*). Estimation of the critical external heat leading to the failure of lithium-ion batteries*. Applied Thermal Engineering 179 (2020) 115665. Elsevier Ltd. https://doi.org/10.1016/j.applthermaleng.2020.115665

Transport Canada (2020). *Canada TDG: Transportation of dangerous goods regulations.* https://tc.canada.ca/en/corporate-services/acts-regulations/list-regulations/transportation-dangerous-goods-regulations

TR_F5_AM_Kiwa Nederland BV. (2017). *Lithium Ion Battery Fire Extinguishment Testing Final Report.*

UL. (2020a). *Batteries for use in electric vehicles* (Standard No. UL 2580). 3rd Ed. https://standardscatalog.ul.com/standards/en/standard_2580_2

UL. (2020b). *Standard for lithium batteries* (Standard No. UL 1642). 6th Ed. https://standardscatalog.ul.com/standards/en/standard_1642

United Nations. (2015). *Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train* (Standard No. E/ECE/324/Rev.1/Add.82/Rev.5).https://op.europa.eu/en/publication-detail/-/publication/fd8e6b47-d767-11e4-9de8-01aa75ed71a1

United Nations. (2019a). *Recommendations on the transport of dangerous goods: Manual of tests and criteria* (Standard No. ST/SG/AC.10/11.Rev.7). https://digitallibrary.un.org/record/3846833?ln=en

United Nations. (2019b). *Recommendations on the transport of dangerous goods: Model regulations, Volume 1* (Standard No. ST/SG/AC.10/Rev.21).https://digitallibrary.un.org/record/3830095?ln=en

United States Office of the Federal Register. (2012). *Code of federal regulations (CFR) Title 49, Parts 100 to 177.* https://www.gpo.gov/fdsys/pkg/CFR-2012-title49-vol2/pdf/CFR-2012-title49-vol2.pdf

Xu J., Guo P., Duan Q., Yu X., Zhang L., Liu Y., Wang Q. (2020). *Experimental study of the effectiveness of three kinds of extinguishing agents on suppressing lithium-ion battery fires.* Applied Thermal Engineering, 171.https://doi.org/10.1016/j.applthermaleng.2020.115076

Yuan L., Dubaniewicz T., Zlochower I., Thomas R., Rayyan N. (2020). *Experimental study on thermal runaway and vented gases of lithium-ion cells.* Process Safety and Environmental Protection, 144, 186-192. https://doi.org/10.1016/j.psep.2020.07.028

Zhang, L., Duan Q., Liu, Y., Xu, J., Sun, J., Xiao, H. & Wang, Q. (2021). *Experimental investigation of water spray on suppressing lithium-ion battery fires.* Fire Safety Journal, 120. https://doi.org/10.1016/j.firesaf.2020.103117

7. CHARGING SYSTEMS AND METHODS

7.1 INTRODUCTION

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. Some mine operations will depend on the availability of fully charged batteries; therefore, sufficient design in the charging system is crucial.

Charging BEVs in mining presents challenges that are absent from the commercial BEV industry because the equipment is much larger and heavier, thus batteries on most mining BEVs require a much higher capacity. Additionally, the mine environment can be harsh because of rough roadways, extreme temperatures, dust, vibration, and concussion from blasting. A given mine will likely employ BEVs from several OEMs, each with different sizes, battery types, and usage profiles. Thus, a hurdle to overcome when introducing BEVs into a mine is a strategy for charging all BEVs.

- Charging Infrastructure, Section 4.6
- Charging Philosophy, Section 4.6.2
- Types of Charging and Connection Interfaces, Section 8
- Charger Performance, Section 9.5

The charger manufacturer and mine operator should communicate about topics such as the durability of the charger in the environment, shock, environmental conditions, temperature ranges, and humidity to make informed decisions and select a charger that is appropriate for the environment.

This section describes considerations pertaining to the charging systems used with mining BEVs and describes different charging methods, summarized in the navigation below.

Note on terminology

Note that while the terms "fast" and "slow" are used to describe power levels throughout this guideline to accommodate the rapid pace of change in charging technologies. There are some existing resources that provide further distinction between power classes, such as CharIN's position paper on DC CSS power classes (2021).

Safety Considerations A general overview of safety considerations associated with chargers.

⚠ Safety by design and guidance on where to look for safety standards.

Charger Installation Provides general guidance on installing charging systems.

⚠ Considerations in this subsection are to make sure the installation and use of the charger is safe.

Incoming Power Provides some general considerations about power requirements.

⚠ Many of these considerations are for hazard prevention.

Types of Charging Methods Provides some guidance and advantages and disadvantages of different charging arrangements, including on-board charging, off-board charging of on-board batteries, off-board charging of off-board batteries (swapping), hybrid methods, proprietary chargers, and alternative systems.

⚠ While the section focuses on the features of these different methods and safety is not the primary consideration, safety by design and hazard mitigation are underlying considerations throughout.

Operation and Controls Provides a brief overview of the components and indicators on the system controls.

⚠ Information on visibility and lighting and emergency shutdown.

Communications and Monitoring Provides charging infrastructure recommendations in order for BEVs to monitor equipment status and communicate to the operator.

⚠ Briefly considers how communications protocols should notify about events such as faults.

7.2 SAFETY CONSIDERATIONS

The charger–BEV interface is a point of interaction between the charging system and BEV operators. Safety features should be compliant with regional safety standards. Ergonomic functionality should be designed to prevent shock and mechanical hazards and avoid physical risk when personnel install, connect, operate, disconnect, and maintain the (initially unfamiliar) charging system. Safeguards should also be in place to prevent the system from moving while plugged in.

- Physical Environment (Charging infrastructure), Section 4.6.5.1
- Charging System Operation and Maintenance, Section 4.6.6

While working with the charging system and in or near the BEV, personnel are exposed to electromagnetic radiation. The International Commission on Non-Ionizing Radiation Protection has several guidelines regarding magnetic field exposure (http://www.icnirp.org/). Chargers should be compliant with regional electromagnetic emission and susceptibility standards.

The jurisdiction has a significant effect on the electrical and safety standards to which the BEV chargers—and 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.

Any additional fire suppression and environmental monitoring requirements associated with the charging system and station should also be considered with reference to existing standards and regulations.

7.3 CHARGER INSTALLATION

It is important that the selected charger is compatible with the energy storage type and chemistry in use at the mine, rated for the appropriate charging rate (slow or fast), and is compatible with different conditions. The charging system enclosure/shell should also have the appropriate environmental protection rating (e.g., NEMA/IP) according to the installation location. The installation of the charger should comply with local codes and undergo any approvals or inspections that are necessary.

- Preparing the Charging Area for Installation, Section 4.6.5.2
- Ventilation and Cooling, Section 4.7

Because BEV batteries require frequent charging, exposure to potential hazards often occurs when personnel connect, operate, and disconnect the charging system. Additionally, the system needs to be monitored so that there are no open plugs.

7.4 INCOMING POWER SYSTEM

The power requirements for a charger will be specified by the charger manufacturer. Some considerations are as follows:

- Location of distribution equipment within a distance that maintains system strength
- Generally, mine power distribution systems with chargers that comply with IEEE-519 or other applicable standards that establish goals for the design of electrical systems, including both linear and non-linear loads
- 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
- Harmonic frequencies produced by chargers and compatibility with other equipment
- A power study is recommended for the overall underground electrical design

- Charging Infrastructure, Section 4.6 (for consideration of the overall infrastructure and planning required to accommodate charging)
- Types of Charging and Connection Interfaces, Section 8 (for further discussion of types of interfaces that are used and the current state of standardization).

7.5 TYPES OF CHARGING METHODS

This subsection provides some guidance on different charging arrangements, design considerations, and their advantages and disadvantages.

7.5.1 On-Board Charging

With an on-board charging from AC supply arrangement, the connection to the BEV is via an AC plug (Figure 7.1). 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 might be required to step the voltage up or down and provide some isolation from the fixed power system.

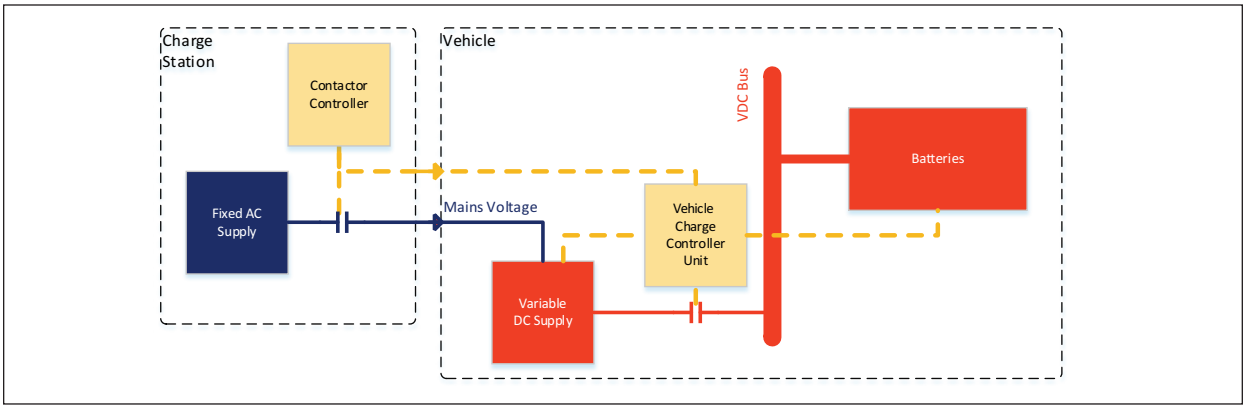


Figure 7.1. Typical On-Board Charging Arrangement

7.5.1.1 Design Considerations

The mine design should include AC connections where BEVs will be parked. The BEV design requires an integrated charger on the BEV, with the plug type chosen that is specific to the mine/jurisdiction. In this configuration, the charging system is not considered separately from the vehicle because it is located on the BEV, and the OEM is responsible for its performance.

In diesel-based mines, one of the first approaches when considering implementing BEVs might be to adapt mobile equipment connectors for drills and bolters. This configuration typically requires very little fixed infrastructure because the configuration involves connecting the charger to the AC supply to charge the equipment. The OEM should supply everything on the BEV (including an on-board charger). In addition to the AC supply, a pilot circuit should be considered (and might be required by some regulations if above a certain voltage level) when power increases. Given that it can be difficult 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 shutdown or appropriate ingress protection to prevent undesired contact.

7.5.1.2 Advantages and Disadvantages

Table 7.1 describes some advantages and disadvantages of on-board charging. Many of the issues listed under disadvantages can potentially 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 can increase because OEM engineers should balance battery and charger size with charging equipment cooling and protection—all while trying to find space for the charger on the various mobile platforms.

Table 7.1. Advantages and Disadvantages of On-Board Charging

Advantages	• The charger is carried with the BEV, eliminating the need to install a separate enclosure within the mine to house the charger. • The charging location is more flexible because a dedicated charging unit in a particular location is not needed to execute a charge. • There is no downtime associated with travelling to specific charger locations or swapping batteries.

Table 7.1. Advantages and Disadvantages of On-Board Charging (continued)

Advantages	• Charging can take place when the vehicle is stationary as part of its duty (e.g. unloading supplies) provided an AC connection is available, thus eliminating downtime for charging. • OEMs are free to optimize the charger and battery arrangement to suit the BEV. • Handshaking and communications between the BEV and the stationary connection are minimized or eliminated. • Barriers to entry for BEVs are reduced, which can be particularly relevant in mixed fleet mines.
Disadvantages	• Potential difficulty for 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 might not be optimal. • The added weight and volume of the on-board charger consumes space and can limit the range of the BEV. • The charging equipment remains with the BEV, where it is exposed to dust, temperature extremes, vibrations, and other harsh operational conditions. • With high-capacity chargers, the power electronics should be cooled while the charge is underway. • Each BEV would likely have a customized charger, increasing the spare parts inventory, maintenance requirements, and repair difficulty compared to standardized off-board chargers. • The power of an on-board charger has practical limits. An off-board approach for high-capacity charging (>100 kW) may be required. • Maintenance of the on-board charger can reduce equipment availability.

7.5.2 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 7.2).

7.5.2.1 Design Considerations

The mine design should include charging stations where BEVs will be parked. The BEV design should specify the charger protocol/plug type. The charging system design should meet specific protocol/plug type, or be proprietary and compatible between the BEV and charging system.

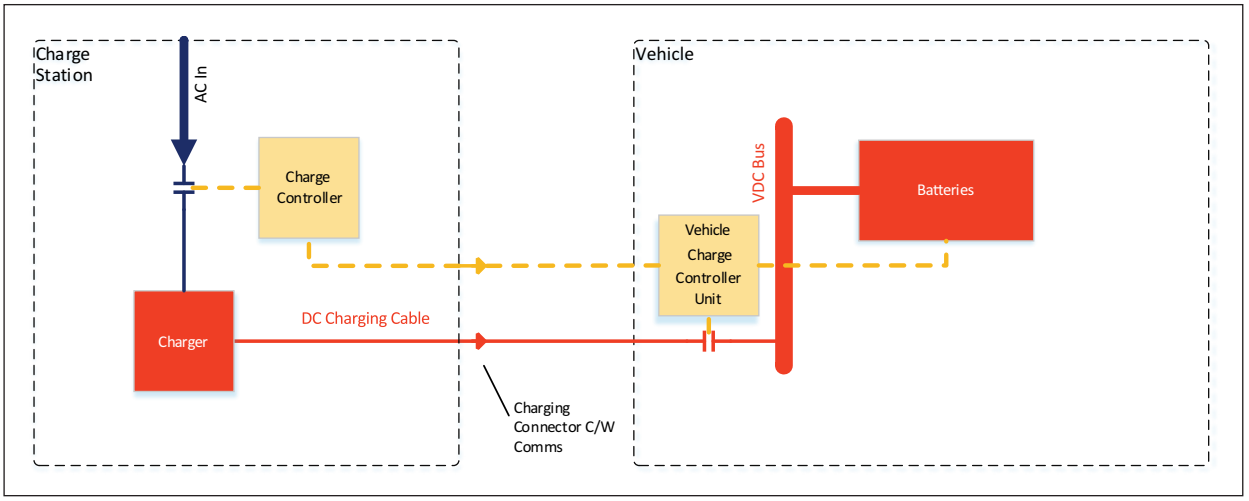


Figure 7.2. Off-Board Charging Arrangement

The charger locations should provide for wayside equipment and 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 that is removed from the BEV.

7.5.2.2 Advantages And Disadvantages

Table 7.2 outlines advantages and disadvantages of off-board charging of on-board batteries.

Table 7.2. Advantages and Disadvantages of Off-Board Charging of On-Board Batteries

Advantages	• BEV size and weight can be lower because charging equipment is not on the BEV. • If practical, chargers can be located in cool and contaminant-free areas. • High-capacity chargers are feasible because size and weight pose less of a challenge. • Multiple chargers can be connected to multiple ports on a single vehicle for even higher rates of charging. • Multiple BEVs can share one charger if connectors and communication protocols are compatible between BEVs. • If interfaces are standardized: – Those in charge of procuring mobile equipment or charging infrastructure can consider mixed fleets. – For equipment operators (instructed persons), a simple and consistent charging interface across the mine can reduce training requirements and operational challenges.
Disadvantages	• Space needs to be allocated in the mine to house charging equipment. • The BEV needs to move to a specific location to charge, which can affect productivity. • Large mines might require many chargers. • Greater potential exists for a variety of chargers, leading to handshaking and communication challenges between the charger and BEV. • Vehicle can potentially need to be out of service for charging.

7.5.3 Off-Board Charging of Off-Board Batteries (Battery Swapping)

With battery swapping, a depleted battery is removed from the BEV and replaced with a fully charged one (Figure 7.3). The BEV can resume work while the depleted battery is charged. The energy density limitations of LIBs mean that swapping can be a viable option if long uphill trips are unavoidable, especially if implementing BEVs in existing mines.

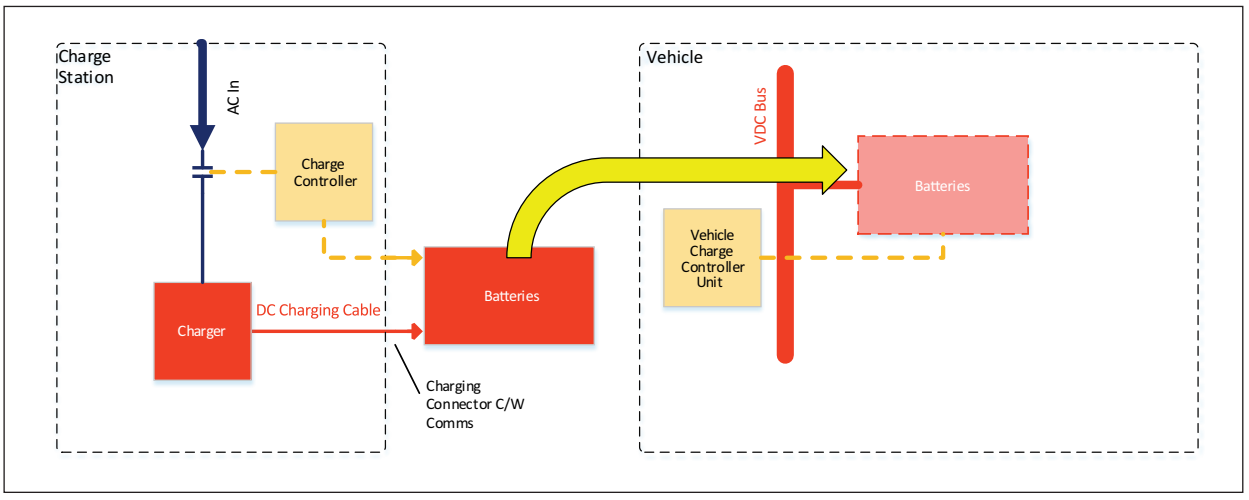


Figure 7.3. Battery Swapping Arrangement

7.5.3.1 Design Considerations

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

7.5.3.2 Advantages and Disadvantages

Table 7.3 identifies some advantages and disadvantages of battery swapping.

Table 7.3. Advantages and Disadvantages of Off-Board Charging of Off-Board Batteries

Advantages	• BEVs can undergo multiple battery swaps in a production shift, which could permit a smaller on-board battery capacity. The battery could be sized to last for short periods and the mining schedule arranged so swap-outs occur at predetermined intervals, which can reduce the cost of ore transport per tonne. • Enables long uphill haulage. • Some charging infrastructure can be eliminated in favour of a swap-out station. • Designated parking for each BEV would not be required. • BEVs do not need to be plugged in at the end of a shift. • Battery maintenance is less likely to affect the availability of the vehicle.
Disadvantages	• Complications 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 could suffer from wear in the mining environment and require a high level of engineering effort to accommodate all types of BEVs. – BEV design options could be limited by the need to facilitate battery removal. • Fixed infrastructure is required: – Dedicated swap-and-charge stations would be needed in strategic locations throughout the mine. – The swap-and-charge infrastructure can be large and mean more mining excavation to house the equipment. – Limited battery charging locations means that much of the mining fleet would need to leave their work areas to pass through the swap-and-charge stations. • Battery inventory management can be 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 if operating a mixed fleet, which can result in management difficulties.

7.5.4 Hybrid Charging Method

A combination of on- and off-board charging arrangements can offer some benefits of both (Figure 7.4). The on-board component is a low-capacity charger that allows the batteries to be charged over a relatively long time span. If a fast charge is required, the BEV is driven to an off-board rapid charger. Proper isolation should 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.

7.5.5 Off-Board Proprietary Chargers

OEMs can choose to develop and supply off-board proprietary chargers for the BEV. The charger is specifically designed for the BEV and is ordered and delivered with it. However, in a mixed BEV fleet, a specific charger for every type of BEV can be challenging. 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 way to address these challenges is to use only one OEM for the BEV drivetrain to standardize the entire mine. However, might limit options.

Proprietary charging solutions can be a useful option in a small-scale BEV deployment or trial.

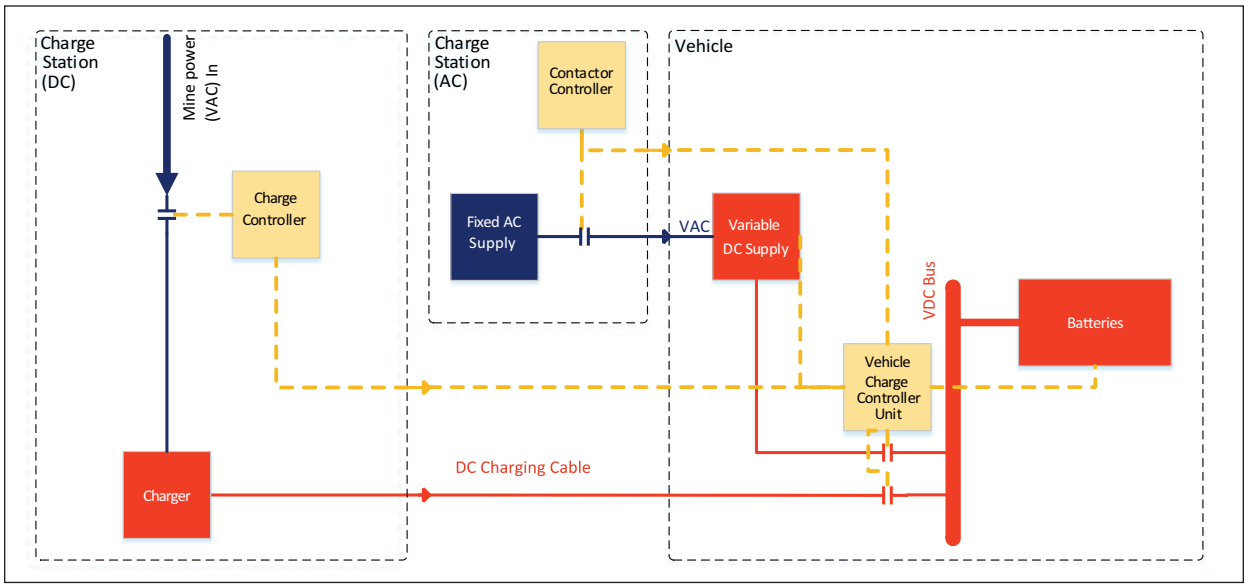


Figure 7.4. Typical Hybrid Charging Arrangement

7.5.6 Alternative Charging Systems and Equipment Types

This subsection describes some alternative charging arrangements on different equipment types.

7.5.6.1 Overhead Catenary Systems Or Trolley Assist

Trolley assist systems have been used in underground mining for many years (especially coal mining). These systems are typically rail mounted and use AC or DC power fed through cables from overhead catenary systems to move ore and personnel 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.

Historically, a risk with some of these systems was that when the pantograph "bounced" along the wires, high-voltage arcing resulted, often debilitating the system through burned out transformers and causing issues with the vehicle.

A recent iteration 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 towards the end of the climb. The trolley system can also be used on the downhill trajectory to inject regenerative energy back

- Trolley Assist Systems (Mine Design), Section 4.2.1.1
- Charge-While-Operating Equipment Group (Mine Design), Section 4.5.1
- Automated Connection Interfaces, 8.3.2 (describes pantograph, inductive, and pin and socket systems)

into the grid. The technology is moving towards a hybrid system, replacing diesel with battery power and automating the alignment and the deployment of the pantograph.

7.5.6.2 Charge-While-Operating (Tethered) Electric Equipment

Charge-while-operating equipment is typically plugged into AC power while performing work, and they travel under battery power when moving between work locations. These systems have been in use for many years and include equipment such as bolters, scalers, jumbos, and drills.

7.6 OPERATION AND CONTROLS

7.6.1 Operator Control Visibility and Lighting

When the charger is connected to the BEV, the BEV gives the charger instructions and minimum and maximum current and voltage limits. The charger complies and provides the requested current and voltage. Status indicators to the operator include:

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

7.6.2 Emergency Stop

An emergency stop button should be provided outside the charger. The button should be sequenced so that 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 emergency stop is required at both locations.

7.7 COMMUNICATIONS AND MONITORING

The open charge point protocol (OCPP) enables BEVs to communicate (i.e., request and confirm) with a central system over the internet in extensible markup language (XML) format. Implementation of an open communication protocol (e.g., OCPP 2.0) is recommended.

It is also recommended that a single charging management software should be adopted on-site to manage charging infrastructure as a whole, regardless of the manufacturer. The software should be capable of load management, reporting and monitoring of charging infrastructure, notification of events (e.g. fault, charge complete) to relevant staff, and prioritization of which vehicle is charged and at what power level if load or charging configuration constraints are imposed.

The charging infrastructure should also be able to communicate with industrial communications protocols (e.g., Modbus, profibus) since most of the mines already have them implemented in their sites. These communications would allow sites to control and monitor the chargers from their existing management platform/software.

7.8 STANDARDS CITED IN THIS SECTION

The following standards are cited throughout the section. The table is not intended to be comprehensive, and not all standards listed will be applicable to all situations. It is the responsibility of the user to reference local regulations and implement the appropriate standard for their situation. The citations listed are for the latest version of the standard at the time of this guideline's publication. Please consult the most recent version of any standard referenced.

Table 7.4 List of Standards Cited in the Charging Systems and Methods Section (listed in the order they are cited)

Section	Industry Standard	Topic	Jurisdiction	Citation
Section 7.4 Incoming Power System	IEEE-519 *IEEE recommended practice and requirements for harmonic control in electric power systems*	Establishes goals for the design of electrical systems that include both linear and non-linear loads	International	Institute of Electrical and Electronics Engineers Standards Association, 2014
Section 7.7 Communications and Monitoring	Open Charge Point Protocol (OCPP) 2.0	Communications protocol that enables BEVs to communicate over the internet in XML	International	Open Charge Alliance, 2018

SECTION REFERENCES

CharIN. (2021). *Position Paper of Charging Interface Initiative e.V. DC CSS Power Classes V7.1.* https://www.charin.global/media/pages/technology/knowledge-base/6539b64483-1624010965/charin_dc_ccs_power_classes.pdf

Institute of Electrical and Electronics Engineers Standards Association. (2014). *IEEE recommended practice and requirements for harmonic control in electric power systems* (Standard No. IEEE-519-2014). https://standards.ieee.org/ieee/519/3710/

Open Charge Alliance (2018). *Open Charge Point Protocol 2.0.* https://www.openchargealliance.org/downloads/

8. TYPES OF CHARGING AND CONNECTION INTERFACES

8.1 INTRODUCTION

When establishing a charging philosophy, standardizing the charging interface as much as possible is ideal in making BEV charging simple, convenient, and safe. While Section 7 provides context on the charging systems and different charging methods, this section provides information on and considerations associated with different types of connection interfaces.

- Charging Infrastructure, Section 4.6
- Charging Systems and Methods, Section 7
- Charger Performance, Section 9.5

Currently, different standard connection interfaces are in place in different regions. Table 8.1 summarizes electric vehicle connection interfaces that are currently used around the world. These interfaces are discussed throughout the section, and standards that are included are referenced to by standard number. Table 8.3 at the end of this section lists the standards in the order that they first appear and provides further information, including the title, description, and citation.

Adopting standards from the commercial BEV industry can be an approach to improving standardization and thereby interoperability between BEVs on a given site. However, the demands of a mining BEV typically differ from those of a passenger BEV. The connectors, charger, voltages, charge rates, and communication methods need to be suitable for a mining BEV drivetrain and battery. In the future, if emerging solutions are not suitable for a mining environment, then the development of a mining interface can be a potential solution. However, achieving agreement on connector type, communication protocol, handshaking, and other details can be challenging.

On-Board Charging from Alternating Current (AC) Supply Interface (Section 8.2) Describes on-board AC connection interfaces defined by IEC 62196.
⚠ Considers safety aspects such as cord length, voltage, isolation, and controls.

Off-Board Charging Interface (Section 8.3) Describes off-board connectors such as CCS type, CHAdeMO, other proprietary chargers, automated connection interfaces, and off-board standardized charging interfaces.
⚠ Not a direct focus on safety, but safety considerations associated with automated connection devices are considered.

Battery Swapping and Charging Interface (Section 8.4) Considers important elements of the interface used to mate the battery to the vehicle and the charger, including durability, power, and interoperability.
⚠ Considers aspects of durability that can affect safety.

Table 8.1. Summary of Types of Existing Connection Interfaces

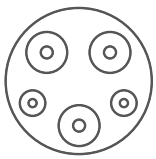
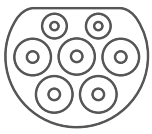
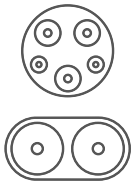
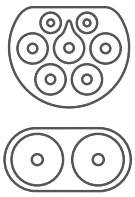
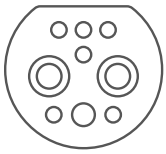
Current type	Connection Type	Description	Image	Region(s)	Cross-reference
AC	SAE J1772 (also referred to as IEC 62196 Type 1)	1 phase and 3 phase AC charging		North America, Japan	See Section 8.2
	IEC 62196 Type 2 Connector (also referred to as Mennekes)	1 phase and 3 phase AC charging		Europe and other markets	See Section 8.2

Table 8.1. Summary of Types of Existing Connection Interfaces (continued)

Current type	Connection Type	Description	Image	Region(s)	Cross-reference
DC	CCS Type 1/ Combo-1 (also referred to as CCS1)	High-power DC charging via dedicated pins		North America, South Korea[1]	See Section 8.3.1
	CCS Type 2/Combo 2 (also referred to as CCS2)	High-power DC charging via dedicated pins		Europe, Greenland, South America, South Africa, Saudi Arabia, Australia, and other markets[2]	See Section 8.3.1
	GB/T 20234	DC charging		China	See Section 8.3.1
	ChAdeMO	DC charging		Japan	See Section 8.3.1

1. Kane (2021) and CharIN (2021a).
2. Kane (2021) and CharIN (2021a). The CharIN recommendation is for the adoption of CCS Type 2/Combo 2 in global markets that do not yet have recommended regulations supporting a specific CCS connector type yet (CharIN, 2020)
Other references for related general information include "Connector Solutions for HEV/AV Charging Systems" (2019); "What is CCS Charging" (Gaton, 2018), and "The Different Types of EV Charging Connector Types" (2019).

8.2 ON-BOARD CHARGING FROM ALTERNATING CURRENT (AC) SUPPLY INTERFACE

During charging, a connector carrying AC is brought to the BEV. The power conversion equipment and most communication needed to regulate charge rates are on-board the BEV. This configuration minimizes the amount of communication needed through the connector between the mobile and stationary equipment.

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 or OEM. The cord set should be easily replaceable in case it is damaged or needs to be longer (i.e., a longer cord is recommended rather than adding an extension).

- On-Board Charging (Charging Systems and Methods), Section 7.5.1

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, IEC 62196-2, and IEC 62196-3 and vary depending on the region. For North America, BEVs have standardized the IEC 62196 Type 1 (SAE J1772) connector. In Europe, a higher capacity Type 2 connector is employed, supporting a higher voltage but lower current, delivering up to 22 kW. See also Table 8.1 for a summary and visuals of these connection interfaces.

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

- Determining whether the plug is inserted into the BEV
- 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.

8.3 OFF-BOARD CHARGING INTERFACE

The following subsections describe manually operated and conductive automated connection devices for off-board charging and consider the options that currently exist.

8.3.1 Manually Operated Connection Interface

The power electronics for converting AC line voltage to DC for charging are 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 can be required.

- Off-Board Charging of On-Board Batteries (Charging Systems and Methods), Section 7.5.2

While the charge is taking place, the BMS needs to constantly vary the current that is 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.

At up to 80% SOC, the BEV will typically 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 requirement contrasts with on-board charging, where communication over the connector is limited to the initial handshaking.

To date, different chargers are regulated in different regions (see Table 8.1 for a summary). Thus, OEMs have responded by accommodating multiple standards on a single charger.

Most widely used in mining BEVs are the two versions of CCSs—Type 1/Combo 1 and Type 2/Combo 2—which differ only in the physical connector (see Table 8.1). Connector types vary by region — CCS Type 1/Combo 1 is used in North American and South Korean markets, and CCS Type 2/Combo 2 is used in European markets and several other global markets, including Greenland, Australia, South America, South Africa, and Saudi Arabia (Kane, 2021 and CharIN, 2021a). CharIN recommends adopting CCS Type 2 Combo 2 in global markets that do not yet have recommended regulations supporting a specific CCS connector type yet (CharIN, 2020). CCS Type 1/Combo 1 and Type 2/Combo 2 protocols support charging current up to 500 A and charging power up to 350 kW (CharIN, 2018; CharIN 2021c).

For an overview of standards related to CCS implementation, see the CharIN basic CCS implementation guide (2021b).

Other DC connectors include:

- CHAdeMO connectors, which have found widespread acceptance in Japan, and are also used in North America and in some parts of Europe (CHAdeMO, 2021). 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).
- GB/T 20234 type connector, implemented in China, capable of 187.5 kW (250 A at 750 VDC).
- Proprietary systems have been developed for the automotive industry.

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

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

Disadvantages include:

- Automotive connectors are plastic
- Limited CHAdeMO voltage (500 VDC)

8.3.1.1 Recommendation for Standardization

A standardized, non-proprietary connection interface is vital to control charging cost and complexity and to enable standardization between mining BEVs. The current approach to standardizing off-board charger interfaces for mining is to use one from the automotive industry. The CCS protocol is currently the most widely adopted standard for off-board charging in mines. It has the following advantages:

- The 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 without a liquid-cooled cable has current ratings up to 200 A, which enables up to 150 kW charging power.
- The CCS cable assembly with a liquid-cooled cable has current ratings up to 500 A, which enables up to 350 kW charging power.
- The latest CCS standard enables up to 500 A for 500 kW charging.
- New versioning (CCS Advanced) needs to be elaborated by CharIN working groups. It currently allows for wireless power transfer (including pantograph) via ISO 15118-8, and reverse power transfer will be enabled with ISO/DIS 15118-20 (currently under development). See the CharIN CCS basic implementation guide (2021b, Figure 1) for a vision of ongoing and future work.

It is recommended to use the CCS type applicable to your region, however, it is currently not possible to implement either CCS type worldwide due to availability and certification requirements.

8.3.1.2 Communication Protocol

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

8.3.2 Automated Connection Interfaces

Automated connection devices can provide the following potential benefits over manual ones:

- **Time savings:** Automated connection devices enable time savings both by providing high-power fast charging at rates over 350 kW and by reducing downtime by limiting the waiting time for drivers to exit when the vehicle stops at the charging station.
- **Greater comfort:** Being able to stay inside the vehicle can improve operator comfort, especially in areas with high temperature and humidity.
- **Reliability:** Automated charging can reduce human error, such as forgetting to plug in and charge the vehicle, thereby rendering the vehicle inoperative for the next driver. When using manual plugs, maintenance technicians often need to replace cords due to regular wear and tear or improper use (e.g., cords left on the ground or in a puddle or accidentally hooked on the mirror as the vehicle drives away).
- **Future-ready:** Having an autonomous vehicle that requires a human to charge it can reduce the benefits of implementing autonomous systems. Automated charging solves this problem and protects infrastructure investments from becoming obsolete as more operations implement autonomous systems.

Some drawbacks that should be considered alongside the above benefits include:

- Higher initial cost
- Greater weight
- Greater number of components with higher complexity

Several standards for automated connection devices have recently been published to support interoperability between various charger manufacturers and OEMs, and others have been in draft form for several years and are expected to see publication soon. Though some of the published standards are written for industries outside of mining (e.g., automotive). For example, conductive automated connection interfaces are standardized in SAE J3015. While many aspects of these standards can be applied to mining, certain aspects, such as the position on the vehicle, might need to be adjusted.

It is recommended to use the same charging interface for both halves of the interface to enable safe operation. Characteristics to consider when choosing a connection interface include:

- Rated voltage according to IEC 60664-1 or other applicable standard
- Rated amperage according to IEC 60364-5-52 or other applicable standard
- Ingress protection when mated or unmated
- Touch protection
- Enclosed versus exposed contacts (Y/N)
- Sequencing (ground contact is first make, last break, control pilot is last make, first break) (Y/N)
- Wire cross-section
- Number of power contacts
- Number of signal contact
- Misalignment tolerance
- Available configurations (i.e., top-down, bottom-up, side)
- Self-cleaning (Y/N)

8.3.2.1 Pantographs

• Alternative Charging Systems and Equipment Types, Section 7.5.6

As an alternative to connector-based charging, pantograph-based systems are being used to charge larger BEVs such as city buses. However, compatibility with an underground mine environment has yet to be evaluated. Pantographs are mechanical linkages connected in a way that the movement of one arm produces identical movements in a second arm. Bottom-up varieties are mounted on-board the BEV and extend upwards to make contact with the charger (Figure 8.1 left). In top-down varieties, the pantograph is mounted on the infrastructure and extends downward onto charging rails on the roof of the BEV (Figure 8.1, right). See Table 8.2 for a comparison between both types. These interfaces are standardized in SAE J3105. 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.

Advantages of pantograph charging include:

- 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

Figure 8.1. Two Pantograph Interfaces Available and Standardized in SAE J3105

Table 8.2. Comparison Between Top-down and Bottom-up Pantograph

Top-down pantograph	Bottom-up pantograph
• Pantograph is off the vehicle (reduced weight) • If pantograph requires maintenance, vehicle is still in service • Spare top-down pantograph is cheaper than spare vehicle for redundancy • Uses the OppCharge standard (https://www.oppcharge.org/), which is less standardized compared to CCS, with more room for interpretation, which can create a longer vehicle integration process with each OEM	• Pantograph is on the vehicle (heavier) • If pantograph requires maintenance, vehicle may be out of service • Uses the CCS protocol, hence vehicle integration and sequential charging are easier

Compliance according to CCS-Mode-4 communication is of key importance. Therefore, a minimum 4-pole design is required for the contact interface with DC+, DC–, protective earth, and control pilot for communication and safety purposes.

A pantograph can have a mechanical connection sequence as described in IEC 62196-3, although it is not required. If no contact order can be guaranteed during an unintentional disconnect, IEC 61851-23 stipulates that a risk assessment should show that no dangerous situation will occur. Note that when the connection is made, no voltage is present on the automatic connection devices (IEC 61851-23).

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 protective earth, while the BEV cannot move if the pantograph is connected. A very fast disconnection time in case of emergency is required. In the second version, with the connection sequence, there are various interfaces (Figure 8.2), such as contact cones, contact rails, and contact hoods, with different sizes depending on the available space on the roof of the vehicle.

Another recently adopted option is to use a bottom-up pantograph to charge BEVs from below (Figure 8.3). 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 for installing contact bars or similar connection interfaces.

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

For all pantograph charging, IEC 61851-23 specifies a minimum distance of 3 m from the surface on which people stand to any touchable live conductors that are not otherwise protected from human contact.

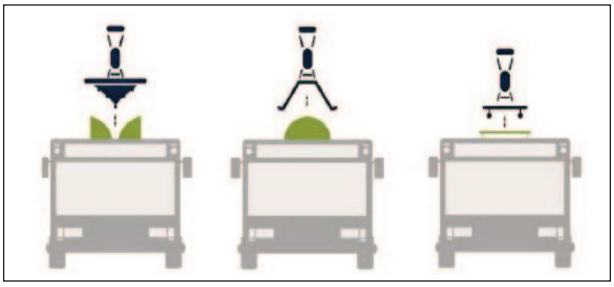


Figure 8.2. Three Interfaces Available for Top-Down Pantographs with Connection Sequence

Figure 8.3. Underbody Charging Using a Bottom-Up Pantograph

8.3.2.2 Inductive Charging Interfaces

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 electromagnetic 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 their precise alignment.

A benefit to inductive charging is that it is done with no cables, wires, plugs, catenaries, or pantographs to install and deploy, making the installation 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.

Currently, two inductive 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 to allow 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 emerging and only experimentally deployed.

8.3.2.3 Automated Enclosed Pin and Socket

The automated enclosed pin and socket interface (Figures 8.4, 8.5, and 8.6) is described in the following published international standards:

- SAE J3105 *Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices* (it is the automated connection device capable of the highest power levels described in this standard, and the only one with touch protection)
- SAE J3105/3: *Enclosed Pin and Socket Connection*
- IEC 61851-23: *Electric vehicle conductive charging system – Part 23: DC electric vehicle charging station*
- IEC 61851-23-1 (in progress): *Electric vehicle conductive charging system - Part 23-1: DC electric vehicle charging station with an automated connection device*
- IEC 63407 (in progress - Previously EN 50696) *Conductive charging of electric vehicles - Contact interface for automated connection device* (ACD)

This connection interface functions by having a flexible plug extend from the charging station, plug into the charging socket installed on the BEV, and initiate charging after a signal is issued (Figure 8.4). This interface is for rapid charging systems currently rated up to 1 MW continuous at 1,000 VDC. A higher power transfer can occur depending on duty cycle and derating based on the specific application, for example this can be used at a power transfer rate of 1.4 MW at 1000 VDC with a 15% duty cycle, or 2 MW+ at 1500 VDC with a 15% duty cycle. These power levels are achieved without liquid cooling, thereby reducing the total cost of ownership and maintenance. It is also 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 entire system is designed to maintain the safety of the operator and other personnel, and it includes safety features like touch protection, contact sequencing, and fully enclosed power contacts. In all situations—whether the system is plugged in or not—all live parts are out of reach of personnel and 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.

Key safety and performance features include:

- The pin side contains the motors and guide rails, the signal connections, and the control box. As the insulator retracts, the contacts are exposed to make it touch-safe.
- The socket contains the replaceable contact elements for the electrical connections.
- The contacts are self-cleaning.
- The pin and socket are fully enclosed to protect nearby personnel from unintended arc flash.

This interface also includes a force sensor that senses if something is obstructing the pin from entering the socket, causing it to retract, thus preventing damage or harm to equipment, vehicles, and personnel.

Misalignment tolerance is achieved by the funnel and rear spring on the pin. If the connection is off centre or approaching at the wrong angle, it will find the centre of the socket. The funnel is attached to the socket and provides misalignment tolerance, and a limit switch can be used to signal that the connector is fully mated and ready for power to flow.

Figure 8.4. Automated Enclosed Pin and Socket Charging Interface

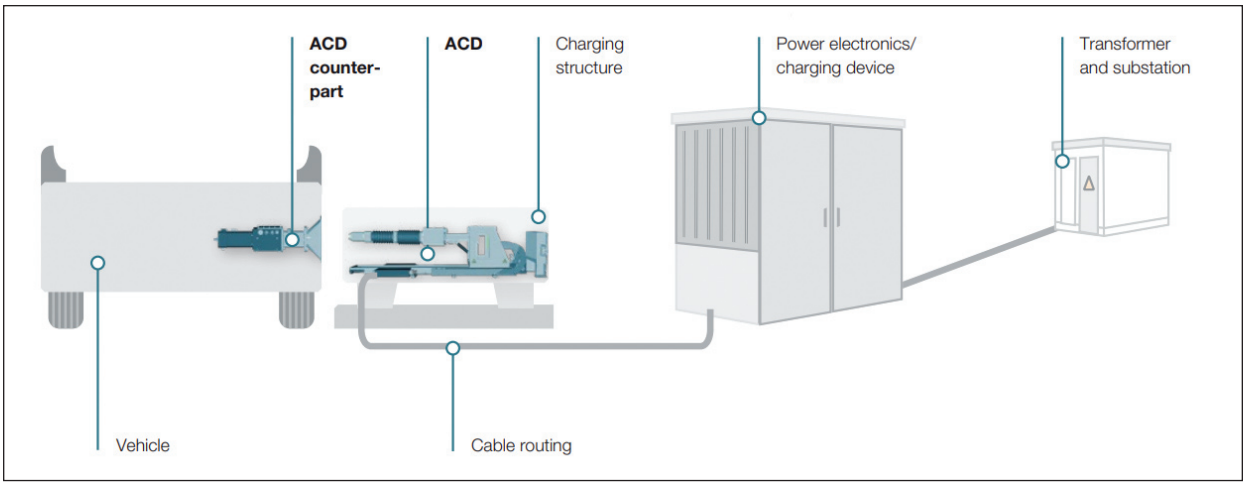


Figure 8.5 Generic Site Layout (adapted with permission from Staubli, 2022)

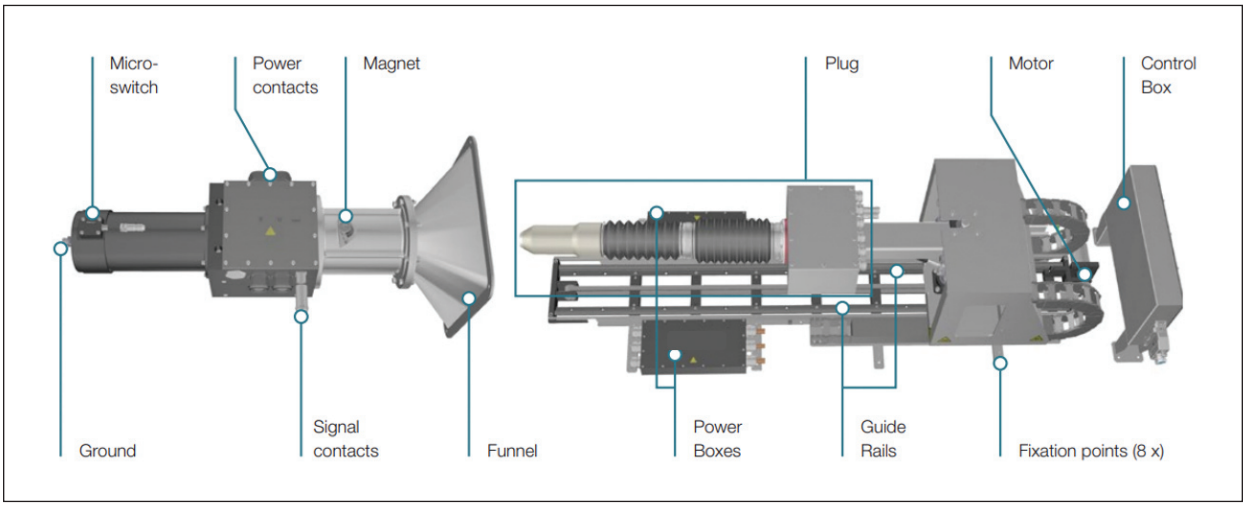


Figure 8.6 Automated Connection Device (ACD) and Socket with Sub-parts (adapted with permission from Staubli, 2022)

8.4 BATTERY SWAPPING AND CHARGING INTERFACE

In a typical battery swapping application, the battery is disconnected from the BEV, then removed via a crane, forklift, or on-board lifting mechanism. Once the battery has been disconnected from the BEV, it is directly connected to the

charger. When the charge is completed, the reverse process is followed to reinstall and reconnect the battery on-board the BEV.

An important consideration for all battery swapping applications is the interface used to mate the battery to the vehicle and the charger. That connection interface is a critical failure point that will experience the most wear of any component in the energy system.

- Off-Board Charging of Off-Board Batteries (Charging Systems and Methods), Section 7.5.3

8.4.1 Durability

In the case of battery swapping, the battery will undergo many connection/disconnection cycles. Therefore, a connector with a high and reliable mating cycle should be considered in order to avoid any failure due to wear. The connector should be able to endure many mating cycles without reduced performance or required maintenance. Ideally, the connector should be sufficiently durable to enable the site to charge as fast as possible to minimize the battery swapping time and improve overall system efficiency.

A connector that has the capability to compensate for some misalignment is recommended in case swapping equipment is not accurate (see Figure 8.7 for an example). Even if there is guidance between the vehicle and charging infrastructure, this guidance is usually not precise enough for a standard connector.

Due to natural wear from handling, vehicle vibration and shock, and dust and dirt in the mine, the durability of the connector is critical. In order to confirm the connector's reliability, it is recommended that a connector for this application conforms to standards that confirm the safe and reliable operation of the overall system (e.g., railway fire protection [EN-45545-2], railway shock and vibration [EN-61373], or other similar standards developed specifically for the BEV industry).

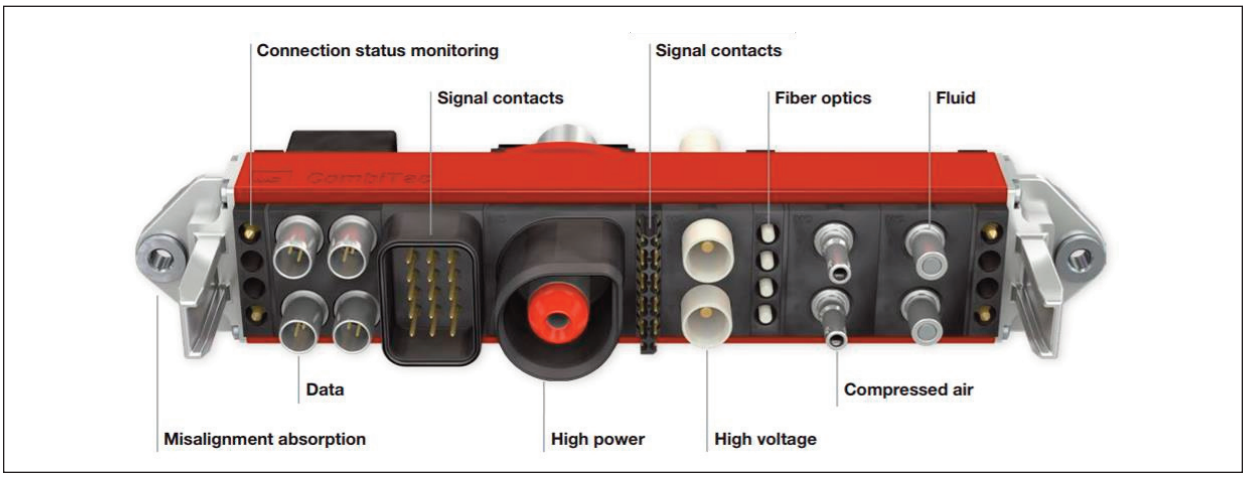


Figure 8.7. Connector Capable of Compensating for Misalignment (Adapted with permission from Staubli, 2019)

8.4.2 Power

Charging in a swapping application typically aims to be as fast as possible so that batteries can be reintroduced to another vehicle with minimal delay and so that fewer overall batteries and less racking space are required. The connector used needs to be able to handle the high power requirements for batteries to be charged at very rapid rates. The connector should be rated for high continuous current and also high short-circuit current. A high continuous current rating enables maximum performance and minimal power loss from heat. The connector should also meet the high short-circuit rating in order to meet several certifications related to energy storage systems. The overall efficiency of the energy system will be largely affected by the contact resistance of the connector. Using connection technology with low resistance across the power contacts is an option for reducing warming and improving the efficiency of the entire energy system.

8.4.3 Interoperability

Unlike typical charging, interoperability for battery swapping depends not only on the connector and the communication behind it but also on the overall form factor of the swappable battery pack and its integration into the vehicle. For that reason, using the same infrastructure for various vehicles can be complicated. Looking at other industries that are already further developed in terms of electrification of vehicles (car industry, buses), interoperability is one of the main reasons why battery swapping is not used as much.

8.5 STANDARDS CITED IN THIS SECTION

The following standards are cited throughout the section. The table is not intended to be comprehensive, and not all standards listed will be applicable to all situations. It is the responsibility of the user to reference local regulations and implement the appropriate standard for their situation. The citations listed are for the latest version of the standard at the time of this guideline's publication. Please consult the most recent version of any standard referenced.

Table 8.3. List of Standards Cited in the Types of Charging and Connection Interfaces Section (listed in the order they are cited)

Section	Industry Standard	Topic	Jurisdiction	Citation
Section 8.1 Introduction Section 8.2 On-Board Charging from Alternating Current (AC) Interface	SAE J1772 *SAE electric vehicle and plug in hybrid electric vehicle conductive charge coupler*	General physical, electrical, functional, and performance requirements to facilitate conductive charging of BEVs and plug in hybrid electric vehicles	North America	SAE International, 2017
Section 8.1 Introduction Section 8.2 On-Board Charging from Alternating Current (AC) Interface	IEC 62196-1 *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 1: General requirements*	Applies to plugs, socket-outlets, vehicle connectors, vehicle inlets and cable assemblies for BEVs	International	International Electrotechnical Commission, 2014b
Section 8.1 Introduction Section 8.2 On-Board Charging from Alternating Current (AC) Interface	IEC 62196-2 *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories*	Applies to plugs, socket-outlets, vehicle connectors and vehicle inlets with pins and contact-tubes of standardized configuration	International	International Electrotechnical Commission, 2016
Section 8.1 Introduction Section 8.2 On-Board Charging from Alternating Current (AC) Interface Section 8.3.2.1 Pantographs	IEC 62196-3 *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 3: Dimensional compatibility and interchangeability requirements for d.c. and a.c./d.c. pin and contact-tube vehicle couplers*	Applies to vehicle couplers with pins and contact-tubes of standardized configuration. Configurations for both CCS interfaces, CHAdeMO, and GB/T are all described in this standard	International	International Electrotechnical Commission, 2014c
Section 8.1 Introduction Section 8.3.1 Manually Operated Connection Interface	GB/T 20234-3 *Connection set of conductive charging for electric vehicles–Part 3: DC charging coupler*	Connection interface standard implemented in China. Part 3 (cited) covers DC charging	China	GB Standards, 2015
Section 8.3.1.1 Recommendation for Standardization	ISO 15118-8 *Road vehicles — Vehicle to grid communication interface — Part 8: Physical layer and data link layer requirements for wireless communication*	Specifies physical and data link layer requirements for wireless communication between electric vehicles and charging systems	International	International Organization for Standardization, 2020

Table 8.3. List of Standards Cited in the Types of Charging and Connection Interfaces Section (listed in the order they are cited) (continued)

Section	Industry Standard	Topic	Jurisdiction	Citation
Section 8.3.2 Automated Connection Interfaces	IEC 60664-1 *Insulation coordination for equipment within low-voltage systems—Part 1: Principles, requirements and tests*	Insulation coordination for equipment within low-voltage systems	International	International Electrotechnical Commission, 2020
Section 8.3.2 Automated Connection Interfaces	IEC 60364-5-52 *Low-voltage electrical installations—Part 5-52: Selection and erection of electrical equipment—Wiring systems*	Selection and erection of wiring systems	International	International Electrotechnical Commission, 2009
Section 8.3.2 Automated Connection Interfaces Section 8.3.2.1 Pantographs Section 8.3.2.3 Automated Enclosed Pin and Socket	SAE J3105 *Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices*	Physical, electrical, functional, testing, and performance requirements for vehicles using a conductive automated connection. There is a main document that references the entire system, and sub-documents for specifics on infrastructure-mounted cross rail connection (J3105/1), vehicle-mounted pantograph connection (J3105/2), and enclosed pin and socket connection (J3105/3)	International	SAE International, 2020
Section 8.3.2.1 Pantographs Section 8.3.2.3 Automated Enclosed Pin and Socket	IEC 61851-23 *Electric vehicle conductive charging system—Part 23: DC electric vehicle charging station*	Requirements for the control of communication between the DC charger and the BEV	International	International Electrotechnical Commission, 2014a
Section 8.3.2.3 Automated Enclosed Pin and Socket	IEC 61851-23-1 Electric vehicle conductive charging system- Part 23-1: DC electric vehicle charging station with an automated connection device	DC electric vehicle charging station with an automated connection device	International	In progress
Section 8.3.2.3 Automated Enclosed Pin and Socket	IEC 63407 *Conductive charging of electric vehicles - Contact interface for automated connection device (ACD).*	(Previously EN 50696) Conductive charging of electric vehicles - Contact interface for automated connection device (ACD).	International	In progress

SECTION REFERENCES

CharIN (2018). *Position Paper of Charging Interface Initiative e.V.* https://www.charin.global/media/pages/technology/knowledge-base/a2d3659f77-1615552583/charin_endorses_increasing_charging_currents_for_battery_electric_passenger_vehicles.pdf

CharIN (2020). *Charging Interface Initiative e.V.* https://www.charin.global/media/pages/technology/knowledge-base/4f8ce6f5d9-1615552574/017charin_one_pager_connectors_used_worldwide.pdf

CharIN (2021a). *CCS Charging Map.* https://www.charin.global/technology/dashboard/

CharIN (2021b). *CharIN Implementation Guide CCS Basic.* https://www.charin.global/technology/ccs-specification/

CharIN (2021c). *CSS Power Classes V7.1.* https://www.charin.global/media/pages/technology/knowledge-base/6539b64483-1624010965/charin_dc_ccs_power_classes.pdf

CHAdeMO (2021). *Fast Charger Maps.* https://www.chademo.com/about-us/fast-charger-maps/

Connector Solutions. (2019). *Connector Solutions for HEV/EV Charging Systems*. Connector Supplier. https://www.connector-supplier.com/connector-solutions-for-hev-ev-charging-challenges/

The Different EV Charging Connector Types. (2019). Enelx.https://evcharging.enelx.com/resources/blog/552-ev-charging-connector-types

Gaton, B. (2018). *What is CCS Charging?* The Drive. https://thedriven.io/2018/12/10/what-is-ccs-charging/

GB Standards. (2015). *Connection set of conductive charging for electric vehicles–Part 3: DC charging coupler* (Standard No. GB/T 20234-3). National Standard of the People's Republic of China. http://www.gbstandards.org/China_standards/GB/GB_T%2020234.3-2015.htm

International Electrotechnical Commission. (2009). *Low-voltage electrical installations—Part 5-52: Selection and erection of electrical equipment—Wiring systems* (Standard No. IEC 60364-5-52:2009). https://webstore.iec.ch/publication/1878

International Electrotechnical Commission. (2014a). Electric vehicle conductive charging system—Part 23: DC electric vehicle charging station (Standard No. IEC 61851-23:2014). https://webstore.iec.ch/publication/6032

International Electrotechnical Commission. (2014b). *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 1: General requirements* (Standard No. IEC 62196-1:2014). https://webstore.iec.ch/publication/6582

International Electrotechnical Commission. (2014c). *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 3: Dimensional compatibility and interchangeability requirements for d.c. and a.c./d.c. pin and contact-tube vehicle couplers* (Standard No. IEC 62196-3:2014). https://webstore.iec.ch/publication/6584

International Electrotechnical Commission. (2016). *Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles—Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories* (Standard No. IEC 62196-2:2016). https://webstore.iec.ch/publication/24204

International Electrotechnical Commission. (2020). *Insulation coordination for equipment within low-voltage systems—Part 1: Principles, requirements and tests* (Standard No. IEC 60664-1:2020). https://webstore.iec.ch/publication/59671

International Organization for Standardization. (2020). *Road vehicles — Vehicle to grid communication interface — Part 8: Physical layer and data link layer requirements for wireless communication* (Standard No. ISO 15118-8). https://www.iso.org/standard/80525.html

Kane, M. (2021) *CCS Combo Charging Standard Map: See Where CCS1 And CCS2 Are Used.* Inside EVs. https://insideevs.com/photo/5601662/phoenix-contact-fast-charging-inlets-ccs-combo-1/

SAE International. (2017). *SAE electric vehicle and plug in hybrid electric vehicle conductive charge coupler* (Standard No. J1772_201710). https://www.sae.org/standards/content/j1772_201710/

SAE International. (2020). *Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices* (Standard No. J3105_202001). https://www.sae.org/standards/content/j3105_202001/

Staubli. (2019). *Modular Connection System.* https://defence.nridigital.com/global_defence_technology_sep19/staubli_electrical_connectors

9. PERFORMANCE STANDARDS

9.1 INTRODUCTION

Once the electric mine is operating, data should be collected and analyzed to assess mine performance. This section describes the types of data and information required to assess the capabilities of battery-powered equipment for underground mines, summarized in the navigation below. The goal of this section 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 descriptions of performance requirements and capabilities can be used to establish common 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 confirm that machines meet the operational goals

Note on safety content in this section

This section does not have a specific safety focus, but performance information can be used to identify and mitigate hazards (e.g., from overheating and performing batteries and chargers).

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. The division of the responsibilities between the operator, OEM, and other parties such as infrastructure and technology providers will depend on the project requirements.

Definitions (Section 9.2) Identifies and defines key terms used throughout this section to compare BEVs to diesel equipment. Terms include: duty cycle, idle/queued periods, availability, utilization, and battery charge time.
Equipment Performance (Section 9.3) Outlines the testing protocol, requirements, and specifications in order to maintain peak equipment performance. Information on equipment performance assessments, regenerative braking systems, ramp conditions, and heat generation is also provided.
Battery Performance (Section 9.4) Contains some examples of battery performance charts, parameters, and specifications to confirm optimal performance.
Charger Performance (Section 9.5) Contains charger performance charts, parameters, and specifications to confirm optimal performance.

9.2 DEFINITIONS

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

9.2.1 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. Instead, it 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).

The duty cycle for BEV equipment is typically more complex than a diesel equivalent. In addition to the typical calculations about travel distances and process time, there is an energy balance to consider. As a result, the evaluation of how the equipment gets its energy and the activities involved in that process (e.g., charging) should also be considered in calculating cycle time. Some considerations to take into account are covered in Table 9.1.

- Mine Layout and Infrastructure, Section 4.2 (impact of duty cycle on design and planning)
- Charging Infrastructure, Section 4.6 (impact of charging time on design and planning)
- Training, Section 4.9 (considers training on performance differences)
- Types of Charging Methods, Section 7.5 (details about advantages and disadvantages of specific methods)

Table 9.1. Duty Cycle Considerations (non-exhaustive)

Plugged in while working with on-board chargers	• *Examples: jumbos, bolters* • Are tramming distances within range of a full battery? • Are there any cases where the equipment has to operate on the battery? • Do on-board chargers have sufficient capacity to fully charge the batteries while operating?
Charging while stationary with on-board chargers	• *Examples: boom trucks, transmixers* • Is there an opportunity to charge while the machine is stationary as part of its job? For example: charging while unloading a boom truck in a storage area • What amount of regeneration can be expected under different payload scenarios? • More opportunity to charge and top up charge
Swapping batteries, and charging the batteries off-board with off-board chargers	• *Example: LHDs, haul trucks* • How long does it take to swap a battery from start to finish? • How long does it take to drive to the swap station? • Any risk of queueing for the swap station? • How many trips can be completed before a battery needs to be swapped? • What amount of regeneration can be expected under different payload scenarios? • Typically higher top speeds and increased acceleration to compensate for charging time
Fast charging batteries on-board the equipment with off-board chargers	• *Example: LHDs, haul trucks* • How long does it take to charge? • How much additional time does it take to drive to the fast charger? • Any risk of queuing for the fast charger? • How many trips can be completed before the battery needs to be charged? • What amount of regeneration can be expected under different payload scenarios? • Typically higher top speeds and increased acceleration to compensate for charging time

9.2.2 Availability and Utilization

Availability is defined as the ability of a piece of equipment to perform its required function over a given period of time. In the case of battery electric equipment, battery charging or swapping hours are considered downtime where the equipment is not available for operation. BEV equipment that is being used as part of its duty cycle while charging is available; (e.g. a jumbo charging while drilling) is available and being utilized. Equipment utilization is defined as a measure of the time a particular piece of equipment is being used.

Common definitions and formulas for the parameters can be found in GMG's *A Standardized Time Classification Framework for Surface Mining* (2020). While this guideline covers statuses and events from surface mining, the time usage model, time category definitions, and key performance indicators (KPIs) also apply to underground mining. The standard time models might need to be expanded to elaborate on how to categorize BEV-associated activities, such as battery charging or swapping.

9.2.3 Idle/Queued Periods

Hypothetically, one duty cycle operates at 100% utilization. However, there are times when the BEV is idle and/or waiting in line while consuming time and energy during a cycle and/or between sequences of cycles. These idle periods (delays) should be accounted for as lost utilization when estimating performance in a fixed time period (e.g., one hour, one shift).

9.2.4 Battery Charge Time

The time required for on-board battery charging or swapping can be significant. If this time period is long, it should be considered downtime because the BEV is unavailable to do useful work. BEVs could have lower availability than diesel equipment, and the added downtime should be considered in planning.

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 is important for the mine operator to measure charging hours and add them to the recorded downtime to accurately assess the impact on availability.

There are scenarios where equipment could still be available while charging if the battery capacity is sufficiently large for its duty cycle with a relatively small charging capacity. For example, a scissor lift that performs light work on a level that is charging from 50% SOC to 70% SOC while the operator can be occupied with another task. In this situation, the machine does not require more energy to complete the work for the remainder of the shift and is available for the operator to use; however, the operator decided to "top up" the battery. Therefore, technology to record charging time—either on-board the machine or battery—and the specific situation should be considered in equipment specifications for BEVs.

9.3 EQUIPMENT PERFORMANCE

9.3.1 General Requirements

• BEV Design, Section 5

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 information will permit mining operators to assess and compare the operational feasibility of various pieces of equipment. This process will reduce uncertainty and discrepancies in performance expectations. It is also recommended that OEMs provide guidance on obtaining performance measurements. The most significant performance requirements that should be understood are:

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

In order to standardize and implement in-field performance protocols for BEVs, operational environmental variables and operational parameters should be considered and defined for the particular applications (see examples in Table 9.2 and Table 9.3). Also, OEMs should list operating criteria/assumptions for the performance data that are communicated to them, such as:

- Road conditions (e.g., rolling resistance)
- 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

Table 9.2. Examples of Environmental Variables

Parameter	Example descriptors or values
Road conditions	Firm, muddy, flexing slightly under load or undulating, maintained regularly, watered, gravel
Rolling resistance	3% (based on situation)
Ambient temperature	Maximum 28°C wet bulb globe temperature in summer Underground temperature throughout the season varies on average between 5 and 45°C; exceptions will need to be addressed accordingly
Other considerations	Humidity, corrosion ratings, ingress, protection ratings, salt resistance, rock falls

Table 9.3. Examples of Operational Parameters

Parameter	Example descriptors or values
Operator skills	At least 5 years experience
Idle periods	Any duration over 10 minutes should be considered
Distance	In metres for each cycle

Table 9.3. Examples of Operational Parameters (continued)

Parameter	Example descriptors or values
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

9.3.2 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 versus continuous ratings:

- **Peak rating:** In terms of diesel equipment, it is the maximum torque that could be generated at zero speed (i.e., stall condition while mucking). A torque converter at this operating point would survive for approximately 5–15 seconds before overheating. The same drivetrain would be capable of running continuously uphill at full power while loaded.
- **Continuous rating:** Should characterize the average energy use for an action; the peak rating often overestimates the value. However, the continuous rating can be a continuous uphill haul. Therefore, the actions that drive continuous versus peak and the frequency of such actions for peak should be clearly stated.

9.3.3 Regenerative Braking Systems

BEVs provide an opportunity to use regenerative braking. The amount of available regenerative braking can benefit the range of a BEV and should be considered in the duty cycle.

The amount of regenerative braking depends on the ramp conditions. Better conditioned ramps have lower rolling resistances, meaning that the operator does not have to use the service brakes as often and can use the drivetrain to recuperate the energy to a greater extent. The amount of regeneration directly affects the duty cycle because it affects the time the BEV can provide work before needing additional energy.

- Regenerative Braking and Ramp Design, Section 4.2.2
- Braking Systems, Section 5.2

9.3.4 Specifications

The OEM should provide comprehensive specifications for the BEV that include performance information in a performance data sheet (see Table 9.4 for an example). These data should be for typical power required at ideal conditions and ambient temperatures, as stated in the data sheets, to assist in understanding the efficiency of the OEM's battery electric drive system.

For basic grade performance data, the units should be kW (power) at the maximum speed (km/h) that is 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 the 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.

9.3.5 Considering Production and Service Requirements

Specifications and data sheets will provide a useful summary of the features of the BEVs, but the various parameters on their own can 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 9.5.

Table 9.4. Typical Performance Data Sheet (example)

Performance Data Power required at maximum speed capable (kW at km/hr)				
	Grade (%)	Estimated or Tested?	Power (kW)	Speed (km/h)
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 required at zero speed with all auxiliary drives operating at max. power		estimated	<10	

RANGE (km)	
loaded at +15% grade	6.9
loaded at 0% grade	40.7

9.3.6 Impact of Tires and Road Surface on BEV Performance

Ramp conditions, particularly for ramp haulage mines, are a key component in vehicle performance, energy requirements, and maintenance requirements. For BEV equipment, speeds can be increased on well-maintained ramps, resulting in reduced cycle times and productivity increases. Energy requirements reduce as a function of rolling resistance.

The importance of well-maintained ramps is therefore amplified with BEVs because the energy balance is part of the duty cycle, whereas this is not typically the case with diesel equipment.

9.3.7 Heat Generation

The ventilation requirements in a diesel mine can be calculated 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

Table 9.5. Overall Performance Data (example, terminology can vary depending on the specifics of the operation)

Description	Details from mining company
Equipment type	40 t haul truck
Heading size	5 m x 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, uphill 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

exhaust gases is usually sufficient to control the heat generated as well, and the mine engineer does not usually need to consider this heat source when sizing ventilation and refrigeration system requirements.

In an electric mine, these emissions are lower, and although less heat is generated, heat is a key "contaminant" that needs to be assessed to determine ventilation and refrigeration requirements for the electric mobile equipment fleet (note that contaminants such as dust and silica and explosive off-gases also need to be managed). The quantity of heat produced depends on continually varying duties of each unit and the efficiency of each vehicle's drivetrain and charging system. Some key concepts to understand are:

- Heat Load (Ventilation and Cooling, Mine Design), Section 4.7.4

- Energy cannot be created or destroyed, it changes from one form to another (The Law of Conservation of Energy).
- 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.
- Zero net work is done if a vehicle returns to its starting point, and the net energy consumed to move the vehicle is lost as heat. Energy used to move material to a higher elevation is put into the potential energy of that material.
- Zero net work is done if a vehicle moves a load on level ground, and all energy consumed is lost as heat.
- While in motion, vehicles require energy to overcome drivetrain, rolling resistance, and auxiliary loads. This kinetic energy is transitional; when the vehicle stops, it is dissipated as heat.

The concepts above indicate that a solid understanding is required of the duty of each unit. In addition, the efficiency of each unit should 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 mine's ventilation flow rates and/or refrigeration requirements.

A benefit of BEVs over diesel vehicles is the significant improvement in efficiency and reduction in heat generation. Figure 9.1 provides an example of a comparison between the efficiencies of each component of the respective drives and the resulting heat losses. Heat generation from a BEV can be as low as 20% of similar diesel equipment.

- Regenerative Braking and Ramp Design, Section 4.2.2
- Braking Systems, Section 5.2

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

allows the vehicle to recuperate some portion of 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 also reused to continue operation. Since a diesel vehicle does not have a large energy storage system (battery), this energy is lost as heat and cannot be reused.

Consider the energy flow when a BEV is hauling a load up a ramp (Figure 9.2). 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:

$$\text{Kinetic energy} = 0.5 \times \text{mass} \times \text{velocity}^2 \quad (1)$$

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

$$\text{Potential energy} = \text{mass} \times \text{acceleration due to gravity} \times \text{height} \quad (2)$$

During deceleration, the kinetic energy can be returned to the battery to be reused 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 t mass that is 2 km up a 17% ramp is approximately 27 kWh.

When the vehicle is hauling down-ramp while 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 energy source can effectively provide fuel for the truck while performing a needed service.

One of the current challenges mine engineers face is obtaining a reliable source of information related to heat generation for specific vehicles. 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., Table 9.4) 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.

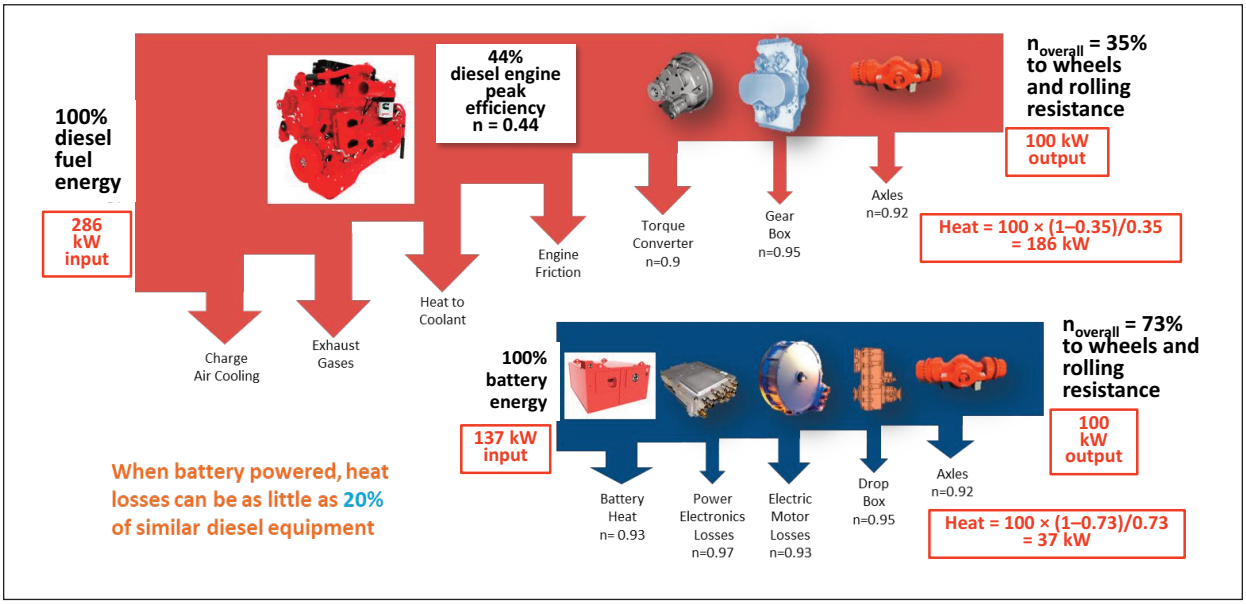


Figure 9.1. Comparison of Heat Generation and Efficiency between Diesel and Battery Electric Vehicles (Example shared by a GMG participant. Data will vary depending on the situation.)

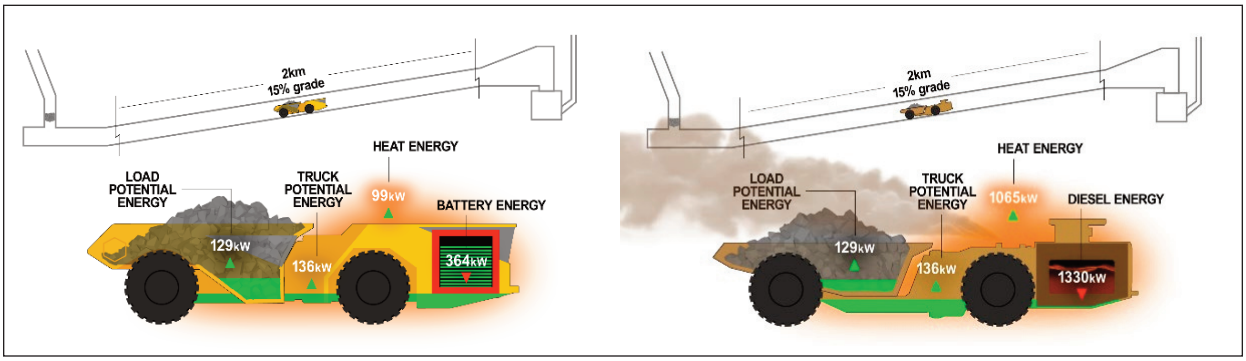


Figure 9.2. Energy Flow for a Battery Electric (left) and Diesel Truck (right)

9.4 BATTERY PERFORMANCE

9.4.1 Performance

• Energy Storage Systems, Section 6

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 that 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 ideally provide the performance specifications based on a hot underground environment. However, this might not be practical. The OEM should indicate—at a minimum—if the proposed battery has been used in such environments and what measures need to be taken to alleviate the impact of heat. This information 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 typically include those indicated in Table 9.6.

Table 9.6. 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 capacity rating from data sheet-does not represent "usable" 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?

Some key considerations around battery degradation performance criteria to factor into analysis when making choices include determining battery life, cycle life, state of health, charge and discharge rates, DOD estimation, and charging temperature estimation.

9.4.2 Specifications

Battery specifications are important for understanding BEV efficiency. With the OEM, the mine operator should define a set of useful parameters relevant to the operation. The OEM should then provide a battery performance data sheet similar to Table 9.7 and performance charts similar to examples shown in Table 9.8 and Figure 9.3. Please note that, as examples, these tables aim to provide detail on the types of data that could be considered, but not all data will always be available and the details that the OEM can provide will vary based on the situation.

9.5 CHARGER PERFORMANCE

9.5.1 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 requirements of the platform so that the infrastructure designers can determine the number and location of charging stations and the ventilation and electrical infrastructure requirements. If battery change-outs are required to meet normal operation requirements, then the OEM should provide details of the excavation size and layout, as well as charging station infrastructure, including lifting equipment and capacity requirements.

9.5.2 Specifications

An example of the basic charging system specification is given in Table 9.9.

Table 9.7. Example of Battery Performance Data Sheet (please note that in some instances the OEM will not always be able to provide all of this information)

Description cell	Details (to be completed by OEM)
Chemistry Specific energy (kWh/kg) Energy density (kWh/m^3) Nominal voltage (V) Amperage (A) Operating voltage (min max V) Cell monitoring system BATTERY: Capacity (Ah) total/usable Power (kWh) total/usable Number of cells Optimal discharge rate (e.g., 0.5°C) Optimal charging rate (e.g., 0.5°C) Maximum charge current (80% SOC) Operating temperature range (°C) Lifespan cycles at % DOD Self-discharge rate (% per month) Memory effect (Y/N)	

Table 9.7. Example of Battery Performance Data Sheet (please note that in some instances the OEM will not always be able to provide all of this information) (continued)

Description cell	Details (to be completed by OEM)
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 9.8. 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 2 cA
Voltage (V) function of charge capacity (%) at normal temperature (21°C): 0.5, 1, and 2 cA
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 2 cA
Lifespan (cycles) function of DOD (%) at: 45, 25, 0, 25, and 55°C

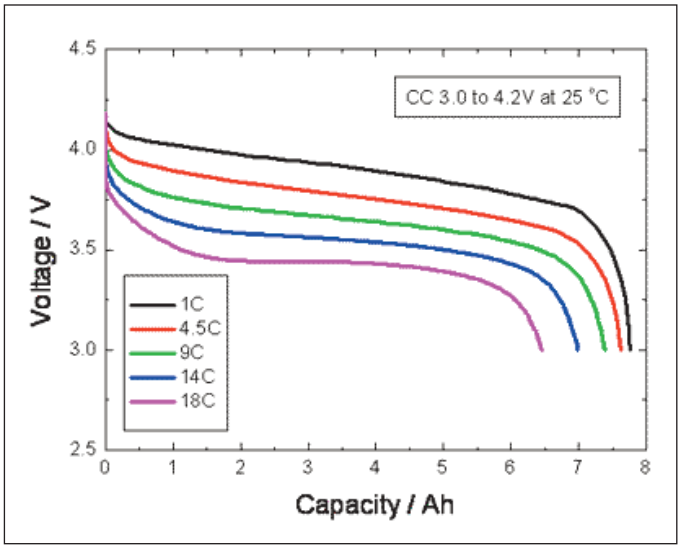


Figure 9.3. Example of a Battery Performance Chart

Table 9.9. Battery Charger Requirements (example, please note that in some instances the OEM will not always be able to provide all of this information)

Description	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) Power factor Charger efficiency Enclosure specifications (e.g., mine duty, NEMA/IP rating) Charge power (based on minimum SOC) Derating of charger capacity (if applicable) Heat rejection of battery charger overvoltage Charging current range	

10. FUTURE WORK

This guideline provides guidance on the adoption of BEVs in mining in its current state. Some items for consideration in future work include discussion around technologies that are advancing rapidly. For example:

- BEVs and autonomous mining and integration
- Non-flammable battery chemistries
- Non-diesel equipment in surface mining

These topics might be covered in future editions of the guideline or might be covered in separate projects. Because of the rapid development of technology in this space, a short revision cycle is planned for this guideline.

Further work to refine the content and structure of the guideline is also suggested for future versions.

The decision-making and prioritization of future work on the topic will be completed by the GMG Electric Mine Working Group.

GLOSSARY

This glossary defines terms as they are used throughout the guideline; it is not intended to be exhaustive.

Air volume: The quantity of airflow in the underground mine. Can also be referred to as airflow quantity.

Availability: The ability of a piece of equipment to perform its required function over a given period of time.

Battery: 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.

Battery charge time: The time required for on-board battery charging or swapping (off-board charging).

Battery electric vehicle (BEV): A mobile, trackless vehicle powered by a battery.

Battery management system (BMS): This system monitors the energy consumed by the BEV during operation, the battery pack voltage, current, SOC, depth of discharge (DOD), and temperature, as well as individual cell voltages.

Battery manufacturer: The manufacturer of the energy storage system (battery).

Battery run-time: The total time a battery can sustain power output.

Braking system definitions:

- **Service brake system:** As defined in ISO 3450 and CAN/CSA-M424.3-M90; can include electric or electro-mechanical braking through the application of dynamic braking.
- **Secondary brake system:** As defined in ISO 3450 and CAN/CSA-M424.3-M90.
- **Park brake system:** As defined in ISO 3450 and CAN/CSA-M424.3-M90; can include electric or electro-mechanical braking through the application of dynamic braking.
- **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.
- **Rheostatic braking:** The generated electrical power is dissipated as heat in brake grid resistors.
- **Regenerative braking:** Using the electric drive motor as a "generator" to convert machine motion into a current that is fed back into the batteries (assuming they have the capacity to accept the energy). Regenerative braking stores kinetic energy lost during deceleration in an electrical storage device such as a battery, or a mechanical device such as a flywheel, for later use.
- **Braking resistor:** A resistive element used to dissipate kinetic energy that was transformed into electrical energy due to "dynamic" or "regenerative" braking.
- **Supply line:** The cable supplying power from the battery to the motor inverter.

Brownfield: A previously developed site that is being redeveloped or refurbished.

Charge-while-operating equipment: Also referred to as tethered, machines that draw power from utility power through a trailing cable.

Charger manufacturer: The manufacturer of the charging system.

Charging philosophy: The approach to charging with the ultimate objective of making charging and operating BEVs as simple, convenient, and safe as refuelling and operating diesel vehicles.

Duty cycle: Includes both the 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).

Energy storage system: see Battery definition.

Equipment utilization: A measure of the time a particular piece of equipment is being used.

Fast charging: Charging with a higher power output that enables a faster charging rate.

Greenfield: New operations built on undeveloped sites.

High voltage: The nominal voltage produced by the main batteries on-board the vehicle, which is typically in the range of 200 to 1000 VDC.

High-voltage DC (HVDC) System: The function of this system is to safely transfer electrical energy from the vehicle's batteries to the various loads, such as the drivetrain, hydraulic systems, DC/DC converters, and other powered devices that can be on-board.

Idle/queued periods: When the BEV is idle and/or waiting in line while consuming time and energy in a cycle and/or between sequences of cycles.

Instructed person: BEV or charger operator (as defined in IEC 60050-826).

Original equipment manufacturer (OEM): The manufacturer of the BEV.

Opportunity charging: The situation where a BEV is stationary for a portion of time as part of its intended duty, and the BEV is charged during that time.

Second life: An end-of-life option for when undamaged batteries with a reduced capacity are reused in applications such as power grid stabilization.

Skilled person: BEV or charger maintenance personnel (as defined in IEC 60050-826).

Slow charging: Charging with a lower power output for slower charging rate.

Specific energy density (energy per unit mass): The capacity to store energy, determining a vehicle's range and capacity to do useful work.

Trolley assist systems: Machines that temporarily draw power from utility power during high load portions of the cycle (e.g., hill climb).

APPENDIX A. REFERENCE CASES

The following reference cases provide some examples of how BEVs compare to diesel vehicles for consideration when building the business case for BEVs. Please note that these are to provide examples and many variables will affect the comparisons.

LHD Reference Case (Mine A)

- 10 t bucket capacity haul uphill loaded (1:7 gradient) 180 m
- 2 x 8 h shifts x 351 days per year
- Battery swap 5 min, 35 loads per battery swap
- Battery life (projected) 16,000 swaps (14 years) from 4,125 swaps to date = greater than
- LHD structural life
- Tire life initially assumed to be the same as diesel but for an unknown reason it is currently 30% more
- Parts–main components 40% less than diesel
- Parts–service items 30% less than diesel
- Parts–oils/lube 40% less than diesel
- Mine ventilation savings–currently none for this one loader test/trial
- Due to the expected challenges with blast fume clearances – the next step in this two year test/trial is working with an OEM for fully autonomous (driverless, controlled from surface central control room) BEVs.

LHD 10 t Reference Case (Mine B)

- 10 t bucket capacity haul uphill loaded (1:7 gradient) 150 m
- Mine traffic speed limit 20 km/h
- 2 x 8 h shifts x 354 days per year
- Battery swap 6.5 min
- 37 loads per battery swap
- Battery life (projected) 16,400 swaps (15 years) from 2,000 swaps to date = greater than
- LHD structural life
- No comment on tire life–assumed same as diesel
- Parts–main components 44% less than diesel
- Parts–service items 28% less than diesel
- Parts–oils/lube 43% less than diesel
- No comment on mine ventilation

Truck 50 t Reference Case (Mine B)

- 50 t carrying (tray) capacity haul loaded 2000 m (1800 m 1:7 uphill plus 200 m flat)
- Mine traffic speed limit 20 km/h
- 2 x 8 h shifts x 354 days per year
- Battery swap 6.5 min
- 3 loads per battery swap
- 5 swaps per shift
- Battery life (projected) 13,680 swaps (12.5 years) from 980 swaps to date
- No comment on tire life–assumed same as diesel
- Parts–main components 45% less cost than diesel
- Parts–service items 39% less cost than diesel
- Parts–oils/lube 53% less cost than diesel
- No comment on mine ventilation

APPENDIX B. EXPLOSION PROTECTION FOR GASSY MINES

Historically, battery- and trolley-powered vehicles have been linked to numerous fatalities caused by underground mine explosions (Dubaniewicz, 2009) in gassy mines. Rescue and recovery teams have encountered electrical ignition sources, including batteries at charging stations and stranded battery-powered vehicles. Explosive methane gas or firedamp can be liberated in underground coal, salt, trona, potash, limestone, copper, and uranium mines (NIOSH 2006). The terms firedamp and methane are sometimes used interchangeably. Firedamp consists mainly of methane, but it also contains small quantities of other gases such as nitrogen, carbon dioxide, and hydrogen. It can also sometimes contain methane and carbon monoxide. Coal dust layers can accumulate on equipment or in entries, posing a fire hazard or explosion enhancement hazard if the dust is carried into the air. Methane ignitions or explosives, for example, can disperse coal dust layers into the atmosphere that subsequently ignite and propagate as powerful explosions.

Explosion protection for mining equipment is needed where the equipment can be exposed to an explosive atmosphere in gassy mines so that the equipment does not become an ignition source for the explosive atmosphere. IEC 60079-0 identifies two categories of equipment used in firedamp-endangered mine workings, M1 (equipment can continue to operate in explosive atmospheres) and M2 (equipment must shut down in the event of an explosive atmosphere). See Stahl (2020, p. 25) for detailed definitions.

BEVs for gassy mines will generally be considered Category M2 equipment. The battery can still be energized after the category M2 equipment has shut down, posing a stranded energy ignition risk to trapped miners and rescue and recovery teams following an initial emergency in which ventilation is disrupted.

There are various methods of providing equipment with explosion protection. Internationally, the methods are called protection types, and they are described by the International Electrotechnical Commission (IEC) 60079 series of standards for electrical equipment in explosive atmospheres. National regulations can differ from IEC standards, and the extent to which the standards apply to a particular country should be verified. A flame-proof enclosure is one protection type that is commonly used in gassy mines. It can withstand an internal explosion of a flammable mixture that has penetrated the interior, without suffering damage and without causing ignition through any joints or structural openings in the enclosure of an external explosive atmosphere that consists of one or more of the gases or vapours for which it is designed. In North America, explosion-proof enclosures are common. Explosion-proof and flame-proof enclosures perform a similar safety function but differ in design requirements because those requirements were developed on different continents. Conventional flame-proof or explosion-proof enclosures for gassy mines prevent ignition of firedamp or methane and coal dust if used in coal mines.

Flame-proof or explosion-proof enclosures considered for enclosing LIBs should also consider the potential for battery thermal runaway. However, IEC 60079-1 does not currently provide design or evaluation criteria for LIB thermal runaway. Dubaniewicz, Zlochower, Barone, Thomas and Yuan (2021, 2022) found that LIBs enclosed within sealed enclosures can produce thermal runaway pressures exceeding minimum pressure containment requirements for conventional flame-proof or explosion-proof enclosures designed for gassy mines. Suggested mitigation strategies include venting with flame arrestors, thermal runaway cascade prevention, and free space provisions to accommodate thermal runaway gas generation. Temperatures measured for iron phosphate cathode lithium-ion cells forced into thermal runaway were below the ignition temperature of methane, which can facilitate the safe venting of thermal runaway gases generated from these cells out of the enclosure and into the mine atmosphere.

REFERENCES

Dubaniewicz Jr. TH. (2009). From Scotia to Brookwood, fatal US underground coal mine explosions ignited in intake air courses. National Institute for Occupational Safety and Health. J. Loss Prevention in the Process Industries. 22:52-58. https://stacks.cdc.gov/view/cdc/9664/cdc_9664_DS1.pdf?

Dubaniewicz TH, Zlochower I, Barone T, Yuan L. (2021). Thermal Runaway Pressures of Iron Phosphate Lithium-Ion Cells as a Function of Free Space Within Sealed Enclosures. Mining, Metallurgy & Exploration 38:539–547

Dubaniewicz TH, Barone TL, Brown CB, Thomas RA. (2022) Comparison of thermal runaway pressures within sealed enclosures for nickel manganese cobalt and iron phosphate cathode lithium-ion cells. Journal of Loss Prevention in the Process Industries 76:104739. https://doi.org/10.1016/j.jlp.2022.104739

International Electrotechnical Commission (2022). *Explosive atmospheres - ALL PARTS* (Standard No. 60079:2022 SER). https://webstore.iec.ch/publication/62417

Kissel, FN. (2006). NIOSH: Mining Publication: Handbook for Methane Control in Mining. Centers for Disease Control and Prevention. Publication No. 2006-127. https://www.cdc.gov/niosh/mining/works/coversheet1459.html

Stahl. (2020). Essential Explosion Protection [Brochure]. https://r-stahl.com/en/global/services-and-seminars/explosion-protection-knowledge/technical-principles

APPENDIX C. BEV GENERAL INFORMATON FORM (EXAMPLE)

Table C.1 provides an example of a general information form about the design of a BEV. Please note that this is an example intended to provide an idea of the type of information included and not intended to prescribe an approach.

Table C.1. BEV General Information Form (example)

BEV General Information Form			
Mining company name		Date (yyyy/mm/dd)	
Mine site		Emergency Phone #	
OEM name		Emergency Phone #	
Make		Model	
Machine type		Manufacturing Date (yyyy/mm/dd)	
OEM unit #		Mine site unit #	
Manufacturing serial number #		Hour	
Auxiliary battery (v)		Master switch location	
Traction battery information			
Package quantity		Location(s)	
Power capacity (kWh)		Max. voltage (V)	
Chemistry		Cell type	
Overall dimension [W/H/L] (m)		Weight (kg)	
Manufacture		MSDS #	
Transport class		Chemical Emergency #	
Emergency disconnect location(s)		High voltage cable colour (s)	
Fire suppressions type		Fire extinguisher size (kg)	
Extinguishing media		Special PPE	
Regenerative brake (Y/N)		Coolant system type	
Battery charger information			
ON/OFF-board		Charge capacity (kWh)	
Charger location(s)		Electrical plug location	
Traction electric motor			
Motor quantity		Location(s)	
Peak power (kW)		Peak torque (Nm)	
Explosive material/fluids information			
Explosive material on-board (Y/N)		Product Manufacturer	
Type		Container quantity (L)	
Hydraulic fluid type		Hydraulic fluid quantity (L)	
Other fluid type		Other fluid quantity (L)	
Air ventilation required (m^3/s)		2/4 wheel-drive	
Vehicle net weight (kg)		Gross weight (kg)	
Vehicle dimension [W/H/L] (m)		Max. operating grade (%)	
Service brake:			
Emergency brake & release pressure:			
Parking brake & release pressure:			
Towing procedure:			
Company representative		Title	