White Paper
Dynamic Charging Interface (DCI)
of CharIN Mining Taskforce

Recommendations and requirements for Dynamic Charging Interface

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Charging Interface
Initiative (CharIN) e.V.
c/o innos GmbH
Kurfürstendamm 11
10719 Berlin Germany

Phone +49 30 288 8388-0
Fax +49 30 288 8388-19
Mail coordination@charin.global

ICMM
34–37 Liverpool Street
London EC2M 7PP
United Kingdom
+44 [0] 20 7467 5070
info@icmm.com
icmm.com

Executive Summary

Dynamic (in-motion) charging is recognized as a key technology for decarbonization in the mining sector. For battery electric haul trucks, dynamic charging allows the haul trucks to charge its on-board batteries and propel using its motors, while it is in motion, thereby ensuring that it maintains their availability or utilization. While for diesel-electric haul trucks, dynamic charging typically reduces the fuel consumption and allows higher speed on grade.

This white paper represents the first iteration in outlining the technical requirements for a dynamic charging interface (DCI) on a mining haul truck. The DCI being the connection point between the haul truck's on-board system and the hardware (e.g., a pantograph, a current collector, or an electrical pick-up device) that transfers the electrical energy from a roadside positioned electrical conductor. The white paper considers the requirements such as electrical safety, functional safety, and hardware interoperability, along with the electrical interface parameters and the design considerations for the interface. Such topics are considered in this white paper, with the goal of achieving a standardized and interoperable interface across the mining industry.

The working group recognizes that achieving this goal will be an iterative process. As a starting point, the white paper considers the DCI on a 'Large' truck (i.e., ranging from the 170 to 300+ metric ton ultra-class surface mining haul trucks), with place-holders for the other truck class sizes. Furthermore, given the rapid pace of technological development in this sector, this white paper captures several 'forward-looking requirements' in anticipation of future developments that should meet those needs.

Besides the technical content, this white paper provides the industry with background information and guidelines for implementation. As the pace of electrification accelerates in the industry, this will serve as a useful resource for future implementation of dynamic charging systems. That is, contributing towards greater standardization and sharing the knowledge to facilitate best practices including safety. This is also a recognition of the work that has been done already – acknowledging that the white paper builds upon some of the pioneering work that has gone before.

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Abbreviations

AC	Alternating Current
AEM	Association of Equipment Manufacturers
AS/NZS	Australian/New Zealand Standards
BEHT	Battery Electric Haul Truck
CharIN	Charging Interface Initiative e. V.
CPO	Charge Point Operator
DC	Direct Current
DCI	Dynamic Charging Interface
DEHT	Diesel Electric Haul Truck
EMS	Energy Management System
EN	Europäische Norm/European Norm (i.e., European Standards)
FMS	Fleet Management System
GVWR	Gross Vehicle Weight Rating
ICMM	International Council on Mining and Metals
IEC	International Electrotechnical Commission
IMD	Insulation Monitoring Device
ISO	International Organization for Standardization
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution (i.e., fourth-generation or 4G wireless standard)
OEM	Original Equipment Manufacturer
PE	Protective Earth
PLC	Powerline communication
SAE	Society of Automotive Engineers
SDO	Standards Developing Organization
SIL	Safety Integrity Level
V2G	Vehicle to Grid
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything (Anything)

Definitions

Note – Where possible, this white paper has tried to align the terms used by other subgroups in the Mining Taskforce. Harmonization of the terms will be a scope for future version of the white paper.

Term	Definition
Dynamic Charging	System to transfer the electrical energy from an overhead or roadside positioned electrical conductor to a mobile equipment, while the mobile equipment is in motion. In the context of a haul truck used in mining: • For DEHTs, this involves propelling the haul truck while it is in motion. • For BEHTs this involves both charging and propelling the haul truck while it is in motion.
Dynamic Charging Interface	Interface is defined to be the connection point between the Power Connector and the Power On-Boarding Module.
Power Connector	Generic term for an apparatus that is used to transfer electrical energy from a roadside positioned electrical conductor to a mobile equipment. This definition is used when describing a pantograph, a current collector (in a trolley assist system) or an electrical pick-up device (in a side rail mounted system).
Power On-Boarding Module	Enclosure(s) on-board the haul truck that distributes to the electrical energy from the Power Connector to the Truck Electrical System. It performs other functions including electrical isolation, protection, and regulation. The Power On-Boarding Module may also perform voltage conversion.
Truck Control System Truck Electrical System	This is the haul truck's electrical system and components. This includes systems such as the DC/DC converters, batteries, and traction system (inverters, motors). Data and communication are handled separately by the Truck Control System.

1. Introduction

1.1. Decarbonization and Interoperability – Driving Forces for the White Paper

Mining companies are increasingly decarbonizing their operations to meet their respective net-zero emission targets. To achieve this target, the industry is exploring a range of solutions, including the adoption of low-emission technologies for power generation, and championing the role of responsibly recovering metals in a circular economy (ICMM, 2024).

An immediate challenge for the mining industry is the greenhouse gas (GHG) emissions from the haul trucks that are used to transport material on a mine site. Diesel-powered haul trucks typically account for 30%–50% of a mine's total energy use, with one study estimating that mining trucks emit 68 million tons of CO_2 ($MtCO_2$) per year (Muralidharan et al., 2019). Therefore, given this scale, there is increasing interest within the mining industry to roll-out zero emission haul trucks.

Concurrently, as the pace of technological development accelerates, it is crucial that the charging solutions for haul trucks are standardized and interoperable. This is to increase safety, foster innovation, reduce duplication, and enhance the operational efficiency and cost-effectiveness of charging solutions for the mining industry (CharIN, 2023). These forces motivated CharIN and ICMM in establishing the Mining Taskforce – as an industry collaboration in addressing the technical issues related to electrifying mining haul truck operations and developing solutions to any technical bottlenecks that may be limiting interoperability.

1.2. Objectives of the White Paper

This white paper's primary objective is to detail the technical requirements for a dynamic (in-motion) charging interface (DCI) on a mining haul truck, with the goal of having a standardized and interoperable interface across the mining industry. Achieving this objective requires careful consideration of this white paper when developing industry standards, OEM-specific designs, or site-specific installations. Also, given the rapid pace of technological development in this sector, this white paper captures some 'forward-looking requirements' in anticipation of future developments that should meet these needs.

Furthermore, the white paper provides the industry with background information and guidelines for implementation. As the pace of electrification accelerates in the industry, this will serve as a useful resource for future implementation of dynamic charging systems. That is, contributing towards greater standardization and sharing the knowledge to facilitate best practices including safety. This is also a recognition of the work that has been done already – acknowledging that the white paper builds upon some of the pioneering work that has gone before.

At a high-level, this white paper considers dynamic charging for:

- Both diesel-electric haul trucks (DEHTs), which represents current state-of-the-art technology, and battery electric haul trucks (BEHTs) that are beginning to emerge in the industry.
- To make this white paper applicable to the broader mining industry, we consider dynamic charging for both surface and underground mining operations, across all commodities – except underground coal.

1.3. Motivation for Electrification and Dynamic Charging

Electrifying the haul fleet is recognized as one crucial pathway that the mining industry can contribute towards achieving global decarbonization objectives (CharIN, 2023). Given the critical role that haul trucks have on a mine site's productivity, the mining sector is seeking charging solutions that minimize impact to the haul truck's availability, or utilization.

Dynamic charging represents one such solution. This white paper defines dynamic charging as the transfer of electrical energy from a roadside positioned electrical conductor to a mobile equipment, while the mobile equipment is in motion[1]. This concept is illustrated using a simplified diagram as shown in Figure 1.1, with trolley assist representing as an example of a dynamic charging system.

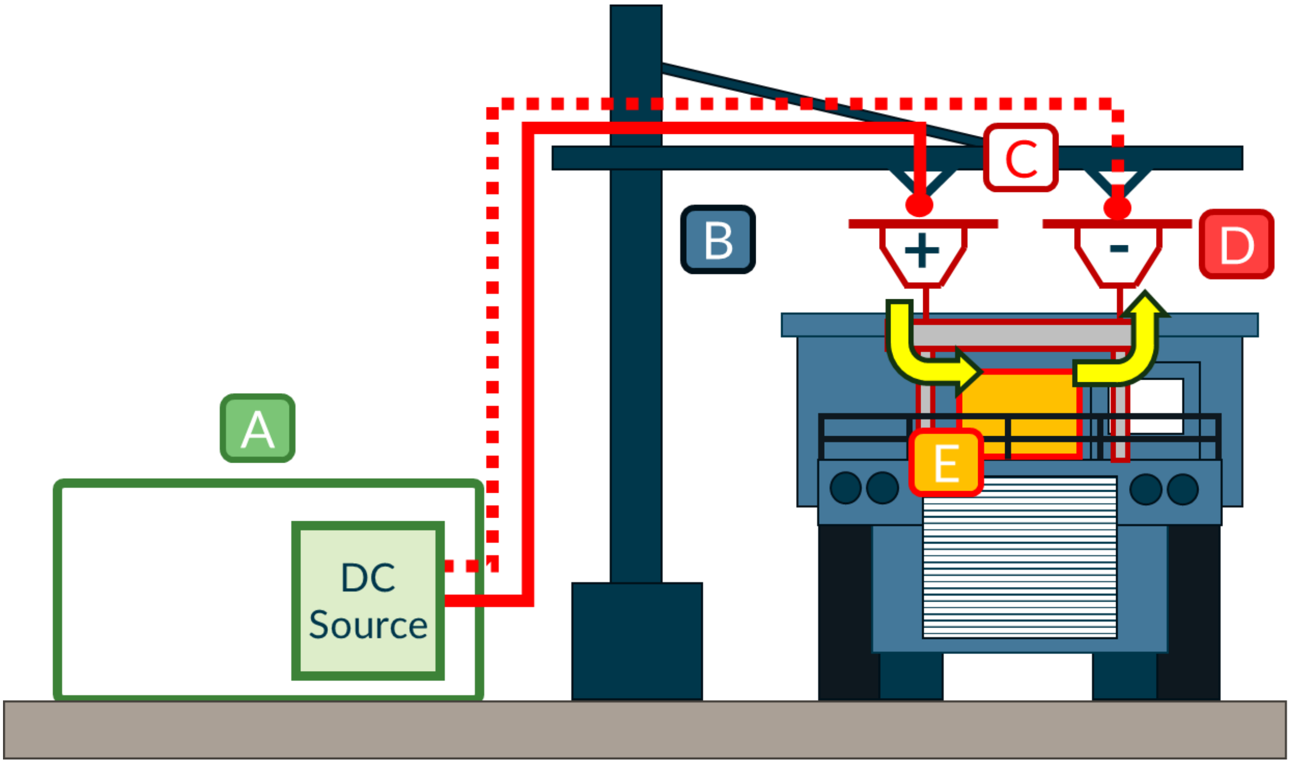

Figure 1.1 Key hardware and components for a dynamic charging system. For the purpose of the illustration, a trolley system is used as an example.

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[1] It may be possible for the haul truck to be charged with the same hardware, while it is stationary. Such dual-use applications are in early stages of consideration. While the white paper captures this application as a future requirement, it focuses on the electrical energy transfer while the haul truck is in motion.

The diagram identifies some of the key elements in a dynamic charging system[2]:

A. Rectifier substation
B. Roadside infrastructure, such as support towers
C. Contact wires or side rails (not shown in Figure 1.1)
D. Power connector, such as the pantograph as shown in Figure 1.1
E. Power On-Boarding Module, which transfers the electrical power to the rest of the haul truck's electrical system. **Dynamic charging interface** is the connection point between the Power connector (D) and the Power On-Boarding Module.

Table 1.1 summarizes the high-level characteristics and benefits of a dynamic charging system. Regardless of the truck type, propulsion power comes from the dynamic charging system instead of on-board energy sources. This provides opportunities for faster speeds and battery charging whilst in-motion.

Haul Truck Type	Haul Truck Operational State	Electrical Power Usage	Benefits
DEHT	Haul truck in motion Connected to contact wires or side rails	Drive system propulsion	Typically, higher speed on grade Lower fuel consumption
BEHT		Drive system propulsion On-board battery charging	Potential speed improvement Improved range (battery charging) Increased utilization compared to static charging (no downtime to charge)

Table 1.1 Benefits of the dynamic charging

1.4. Mining Taskforce's Dynamic Charging Interface Subgroup – Objectives

The DCI subgroup was established in early 2023, as one of the Mining Taskforce's five workstreams. The subgroup collaborates on the electrical, mechanical and communication interface requirements for transferring energy between a moving haul truck and the mine site's power infrastructure.

The subgroup's objectives include:

- Reaching a common understanding and agreement on the technical interface (electrical, mechanical and communication) for onboard charging systems allowing dynamic and stationary charging operation for each truck class sizes.
- Identifying the use cases, truck classes and scenarios for dynamic charging, while defining the boundaries of the technology and solution.

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[2] Section 9 provides further technical details on the elements shown in Figure 1.1.

The subgroup's long-term objective is to provide input to facilitate future development by a standards developing organization (SDO) of a standard/guideline for the DCI on the mining haul trucks. By achieving this objective, it will deliver standardization and interoperability on the haul trucks, and also develop a standard that is 'fit-for-purpose' for the mining industry. At present such a standard does not exist and therefore the industry needs to look at relevant standards from the adjacent sectors (namely railway and even trolley buses), when seeking guidance on the requirements for dynamic charging. For example, the IEC 60077-3 *Railway Applications – Electric equipment for rolling stock – Part 3: Electrotechnical components – Rules for DC circuit-breakers*, EN 50119 *Railway applications - Fixed installations - Electric traction overhead contact lines* or EN 50502 *Railway Applications - Rolling Stock - Electric Equipment In Trolley Buses - Safety Requirements and Current Collection Systems.*

The subgroup envisages that the standards/guideline can be applied to the wide range of current and upcoming haul trucks in the mining sector. Referring to the truck size categories in Section 2.1, this ranges from the 'Large' trucks (i.e., ranging from the 170 to 300+ metric ton ultra-class surface mining haul trucks) to the 20-40 metric ton 'Small (Underground)' trucks used in underground metalliferous mining.

This white paper captures the work by the DCI subgroup during 2023, in detailing the technical elements of the interface for the initial use case. Additionally, this paper presents a roadmap for the next stages, and captures the requirements for future consideration.

1.5. Exclusions

As briefly explained below, the following items are currently out-of-scope for the subgroup, and therefore excluded from this white paper.

- **Hydrogen fuel cell haul truck.** While dynamic charging is technologically possible on a hydrogen fuel cell haul truck, the fuel cell effectively provides the dynamic charging capability. Therefore, the subgroup doesn't see this being a critical need in the immediate timeframe.
- **Haul trucks using non-hydrocarbon-based fuels.** While DEHTs are within the scope of this white paper (and represent the present state-of-the-art technology), haul trucks using 'exotic' fuels such as hydrogen and ammonia have been excluded. This exclusion is given the low readiness of such technologies, combined with the uncertainty of their commercial viability.
- **Underground coal.** This white paper considers application of dynamic charging across the broader mining industry (commodity types, surface and underground). However, for the reasons as mentioned in Section 2.3, application of dynamic charging in underground coal has been excluded.
- **Other vehicles besides haul trucks.** The subgroup recognizes that other mining vehicles (e.g., surface graders) may become electrified in the future and may benefit from having dynamic charging capabilities. However, given the critical importance of haul trucks to mining operations, and to keep the scope well defined, the white paper only considers dynamic charging for the haul trucks.
- **Mine site's electrical infrastructure.** The group acknowledges that for the dynamic charging system to be successfully implemented on a mine site, a reliable and resilient electrical network is crucial. Achieving this, for example, may require installing additional back-up generation capacity

and/or energy storage systems. While this is an important topic, consideration of the mine site's electrical infrastructure goes beyond the subgroup's current focus – which is the DCI on-board the haul truck.

- **Civil structures and earthworks.** Extending from the above point are civil structures (e.g., concrete slab foundations) and earthworks (e.g., excavations or windrows/berms) for electrical infrastructure associated with the dynamic charging systems.
- **AC systems.** High-voltage AC systems (e.g., 25 kV AC) are common across the global railway sector, as it allows higher power capacity. However, given the difference in the application profile between a haul truck and a train, the subgroup doesn't anticipate high-voltage AC systems being used in dynamic charging in the immediate timeframe. This reflects the weight penalty associated with the installation of additional hardware (e.g., rectification system) on board the haul truck to take advantage of the high-voltage AC. This takes away from the haul truck's payload capacity – which is its primary function.
- **Power Connector systems (e.g., pantographs, current collector, pick-up device).** Specifications relating to the Power Connector system[3] is beyond the scope of this subgroup. This is given that some systems are already commercially available, there are relevant standards in the railway industry, and not to restrain innovation for new solutions. But given that such systems need to work as a part of an overall solution, we do provide some suggestions that may assist the manufacturers – for use in a mining application or to better integrate with the DCI.
- **Adaptions to extreme environmental conditions.** Given the geographical diverse nature of the mining industry, wide range of operating conditions may be encountered. The white paper proposes the DCI performance based on what is recognized as common operating conditions. Any extreme conditions, beyond what is outlined, are perceived to be beyond the scope of this white paper.
- **Protocols for exchange of data between the systems.** The subgroup will utilize the commonly used protocols for exchanging data between the systems. We also note there is a separate work to be undertaken by the Mining Taskforce to explore the protocols that are fit-for-purpose for charging systems in mining applications.

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[3] This is the term the white paper is using to describe pantographs, current collectors, and electrical pick-up device.

2. Scope

For the white paper to define the DCI's technical requirements, we outline how and where dynamic charging will be used, thereby providing the necessary context. This section discusses the scope of the dynamic charging that will be considered in this white paper, which considers factors such as the *haul truck class size*, *dynamic charging technology* and *mining application*.

2.1. Haul Truck Class Size Classification

Figure 2.1 illustrates the range of truck class sizes to be considered by the DCI subgroup. As shown in the diagram, there is experience with dynamic charging (trolley assist) across all the truck class sizes.

Figure 2.1 Range of truck class sizes to be considered by the DCI subgroup. Images courtesy of Boliden ('Large' size truck), Liebherr ('Medium' size truck), Epiroc ('Small (UG)' size truck) and Scania ('Small (On-road)' size truck).

The white paper classifies the haul trucks into the following categories:

- **Large –** Trucks that are in the Association of Equipment Manufacturers' (AEM[4]) EM08 category ('rigid frame haulers'), with the payload greater than 170 metric ton. These trucks are used in surface mining operations.
- **Medium –** Trucks that are in the AEM's EM08 category ('rigid frame haulers'), with the payload less than 170 metric ton. These trucks are used in surface mining operations.
- **Small (Underground)** – Trucks that are in the AEM's EM80 category ('underground haulers')
- **Small (On-road)** – Trucks that classified as 'Class 8' as according to US GVWR classifications. These trucks are used in surface mining operations.

As mentioned, this white paper considers dynamic charging for both DEHTs, which represents current state-of-the-art technology, and BEHTs that are starting to emerge in the industry.

While the white paper provides general technical requirements for the DCI that is applicable across all the haul truck categories (Section 6), it focuses on the 'Large' and 'Medium' haul truck categories given:

- Participation in the subgroup by the OEMs from the 'Large' and 'Medium' category of haul trucks (Caterpillar, Liebherr and Komatsu). Therefore, this allowed the necessary technical input which has been valuable in shaping the proposed technical requirements for the DCI.
- Existing experience with dynamic charging (trolley assist) in several mining operations.

We recommend that the following topics are considered in a future version of the white paper:

Future Works – Other Truck Class Sizes

The CharIN/ICMM Mining Taskforce has been established to accelerate the adoption of electrifying mining haul truck operations and address the technical bottlenecks around the interoperability. Consistent with this objective, the DCI subgroup aims to provide the technical requirements for DCI across all the haul truck categories. For the 'Small (UG)' and 'Small (On-road)' Epiroc and Scania have participated and contributed to this white paper. Having Epiroc and Scania's peers join the subgroup will be beneficial as this will motivate an industry wide technical discussion (much like what was achieved for the 'Large' and 'Medium' truck categories).

Future Works – Other Equipment Type

The white paper has intentionally focused on haul trucks, as these equipment types are responsible for significant direct carbon emissions at a mine site (as highlighted in Section 1.3). But we acknowledge that the technical requirements for the DCI can potentially be applied to a wide range of other mining mobile equipment. Therefore, the DCI subgroup may wish to consider other mining mobile equipment as part of its future works.

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[4] We acknowledge the AEM's assistance with this.

2.2. Dynamic Charging Technology

While the subgroup is focused on the interface, to provide context for the discussion, we need to consider the ‘bigger picture’ and consider the dynamic charging technologies. This white paper considers the following two dynamic charging technologies, as illustrated in Figure 2.2.

These technologies have been selected, based on either existing implementations or potential likelihood of being used in a mining application.

- **Trolley Assist –**Electrical power is transferred to the haul truck either through a current collector that connects to an overhead catenary or a ‘trolley line’. The current collector could be either a pantograph (as seen on a train or a tram) or current collector heads mounted on a trolley pole (as seen on a trolley bus). Trolley assist systems have already been deployed at several mine sites for DEHTs, with example implementations described in Sections 3.1 and 3.2.
- **Side Rail Mounted –** Electrical power is transferred to the haul truck through an electrical pick-up that connects to an electrical conductor that is mounted on the side of the haul road. This is similar to the ‘third rail’ solutions in some railway/metro systems. But the difference is that in a rail application the return/ground is provided through the wheel-rail interface. Haul truck applications require at least two conductors on the side rail – for power and return.

Figure 2.2 Dynamic charging technologies considered by this paper. Trolley assist systems (image courtesy of Komatsu) and side rail mounted system (image courtesy of BluVein).

Both technologies must be capable of supporting DEHTs and BEHTs. Dynamic charging allows DEHTs to reduce their diesel fuel usage when connected to the electrical conductor, by using the electrical power to propel the haul truck, and in some cases to travel faster when travelling uphill on-grade. For BEHTs, the haul truck will need to be capable of charging, in addition to propelling, while connected to the electrical conductors.

To keep the terminology consistent, this white paper uses the term **‘Power Connector’** when referring to the pantograph or current collector in a trolley assist system, and the electrical pick-up in a side rail mounted system.

Besides the trolley assist and side rail mounted systems, there are other dynamic charging technologies that have been developed for the automotive and heavy-duty on-road markets. We provide a brief reason below why these technologies have been excluded from the subgroup's consideration for this white paper:

- **Ground-mounted conductor system –** Conductive rails are installed on the road, with the electrical pick-up travelling on the ground. This is not seen as being practical in a mining environment given the roadway conditions on a mine site (i.e., unsealed, dusty). Also, because the conductive rails need to be installed into the roadway, additional earthwork is required. This presents greater challenges for use in certain commodities where the haul road location changes with mining operations.
- **Wireless (inductive) charging system –** Like the ground-mounted conductor system, installation on the road makes this technology less feasible. Furthermore, being a wireless system, the power transfer capability is lower than a conductive solution.
- **Opportunity charging** – This is a hybridization of static and dynamic charging. It is effective in certain applications such as public transport. For example, when a battery-electric bus arrives at a stop, while the passengers are boarding or alighting, the pantograph is extended to charge the bus. The pantograph could be installed either on the bus or on the charging infrastructure (this is known as a 'reverse pantograph'). Such systems are commercially available and technical requirements for this are detailed in SAE J3105 *Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices*. However, given the need to maximize equipment utilization in mining, this solution doesn't appear to be practical for most mining applications.

However, given the rapid pace of technological development in this sector, the subgroup will keep an open mind about the dynamic charging technologies that have been excluded from this white paper. Provided there is a compelling use case/application that can be identified or brought forward by the industry, the subgroup is open to these technologies being included in future scope.

2.3. Mining Application

The guideline proposed by the DCI subgroup also needs to consider the mining application of the dynamic charging solution. Given the participation by the 'Large' and 'Medium' category of haul trucks OEMs (Section 2.1) the subgroup has initially focused on surface mining applications across all mined commodity types. Once there is sufficient participation by the 'Small (UG)' truck category OEMs the subgroup will extend its focus to underground metalliferous mining applications.

The subgroup will not develop a standard/guideline for underground coal application. This is given the unique engineering designs and controls that are necessary for operation in such a hazardous environment. For example, meeting the requirements as outlined in the IEC 60079 *Explosive atmospheres* series of standards, along with any jurisdiction specific legislation (e.g., *Coal Mining Safety and Health Regulation 2017 (Qld))*.

3. Example Implementations

Across the truck sizes there are well known implementations in the mining industry, while for the ‘Small (On-road)’ class, Germany’s electric-highway is a well-referenced system. This section provides an overview of these implementations. This is to inform the industry about what has already been done, thereby providing a concrete example for the use cases, and also to highlight that dynamic charging is applicable to a wide range of truck class sizes and mining applications.

3.1. ‘Large’ Trucks – Aitik Mine (Boliden Mineral AB)

Aitik mine, which is owned and operated by Boliden Mineral AB, is Sweden's largest open-pit copper mine (Boliden, n.d.). It is also known for the trolley assist (dynamic-charging) system that has been implemented for the ‘Large’ size truck class, along with the first implementation of an electric road for haul trucks in the arctic environment (Lindgren et al., 2022). Since its successful implementation at Aitik, Boliden has expanded rolling-out the trolley assist to Kevitsa mine.

An initial pilot project to implement trolley assist at Aitik commenced in 2017. Four Caterpillar 795F AC haul trucks were initially modified for trolley assist operation (as shown in Figure 3.1) and a 700 m long test lane was built, commissioned in 2018. Given the promising results, a decision was made in late 2019 to expand the project – to modify 10 more trucks for trolley assist operation and expand the trolley assist haul route to 1.6 km (including the test lane).

While connected to the trolley, the haul truck can draw 4,500 kW from the electrical system (Lindgren et al., 2022) while the fuel consumption and emissions are reduced by 80-90%. Furthermore, while being connected to the trolley, speed-on-grade increased as much as 100 percent versus diesel-only mode. While using the trolley, a loaded 795F could operate at 28 km/h on a 10 percent physical grade with solid haul road conditions (Caterpillar, 2020).

Figure 3.1 Caterpillar 795F AC haul truck at Boliden Mineral AB’s Aitik Mine (image by Mats Hillblom, courtesy of Boliden).

3.2. ‘Medium’ Trucks – VA Erzberg

Erzberg mine (owned and operated by VA Erzberg GmbH), located in the Styria region in Austria, is the largest hard rock mine in central Europe. Erzberg mine has implemented a trolley assist system for its fleet of 100 ton ‘Medium’ size trucks (7x Liebherr T236) – with one such truck shown in Figure 3.2. The trolley system implemented at Erzberg is known for several unique features. It has been designed for the extreme weather conditions of the Austrian Alps and maneuverability of the machinery via a 180° switchback. Using the information provided in the articles by Schimek et al., (2022; 2023), this section provides an overview of the implementation of the trolley system at the Erzberg mine.

Figure 3.2 Liebherr T236 haul truck at the Erzberg Mine (image courtesy of Liebherr).

As seen in Figure 3.2, the trolley system was designed with a doubly insulated catenary line and standard components from the trolleybus sector, such as the current collector system (this is different to a pantograph). Other details include:

- The contact wire voltage of 900 V DC +/- 200 V, with all components designed for a nominal operating voltage of 1500 V DC and a continuous load of 3000 A. Depending on the catenary voltage (e.g. primary voltage, number of vehicles in the overhead line, distance to the nearest rectifier station, etc.), each T236 can draw between 1300 and 1500 A from the overhead line.
- From an electrical infrastructure perspective, the substations have been designed with a short-term peak current flow of 6000 A (at the rectifier). This allows at least three trucks to operate directly behind each other in every section of the catenary line.
- The overall catenary network covers 4.7 km of ramps with three substations (3 MVA) that are galvanic connected via busbars. The longest consecutive line (3.8 km in length) has been divided

into three sections via diode insulators, allowing maintenance work to be performed on individual sections of the line without having to shut down the entire system.
- The longest catenary line follows the main road which comprises of a 180° switchback and several curves with radii as low as 13m. Several secondary roadways join the main catenary line at different points.

When the truck approaches the entrance gate to the trolley system, the operator activates the 'trolley mode' by pressing a button within the cabin. This automatically moves the current collector heads to the highest possible position and are spread at a distance of 2.0 m. Also, a speed limiter is automatically activated to 7 km/h during the aiming process, which allows the driver to fully concentrate on "aiming" the target to reach the entry funnels. Once the current collector heads have been in contact with the entrance guide, the actuators for the horizontal and vertical movements of the rods are deactivated and only the force of preloaded springs ensures good contact between the current collector head and the contact wire.

As soon as the vehicle is connected to the overhead line and the catenary voltage is detected, the diesel generator operation is shut down and the power supply from the overhead line is ramped up at the same time. The mechanical connection (and disconnection) is done at 0 A. In addition, the generator is put into engine operation via the overhead line, which drives the pump transfer case and pushes the diesel engine to 1300 rpm. As a result, it is operated with almost zero fuel consumption. This system requires around 150 kW of additional electrical energy from the overhead line.

On the T236 a trolley control box has been installed for smooth switching of operating modes. A DC circuit breaker protects the electrical system against overload and short circuit. The current collector heads are geometrically very similar to those of trolleybuses – but due to the higher currents to be transmitted, new sliding elements with much higher metal content were developed. The possible swivel range with the installed configuration is horizontal ±3.0 m and vertical ±0.5 m.

3.3. 'Small (UG)' Trucks – Kiruna Trucks

While there's significant interest currently for BEHTs in underground metalliferous mining, the 'Kiruna Truck' remains the only commercialized dynamic charging system for the 'Small (UG)' truck class category. The 'Kiruna Truck' first appeared in the mining sector around the mid-1980s (Paraszczak et al., 2014a). Initially manufactured by Kiruna Truck Company, which was later acquired by GIA and then Atlas Copco (forerunner to Epiroc). The 'Kiruna Truck' was implemented across different mine sites in Sweden, Canada, Australia, Spain, USA and Kazakhstan (Paraszczak et al., 2014b), it is still in operation in Canada.

The 'Kiruna Truck' was offered as a 35-tonne (EMT-35) or a 50-tonne (EMT-50) truck. Interestingly the first version of the 'Kiruna Truck' was a BEHT, having an on-board battery pack for operation when not connected to the rails, which then powered DC motors. Later version of the truck used a Tier 3 auxiliary diesel generator instead and AC motors. For both versions, dynamic charging relied on the truck drawing power from roof-mounted (overhead) three-phase 690V AC supply line, which consisted of three 50 mm copper tubes and two square section guide rails. This can be seen in Figure 3.3.

Like the surface mining trucks, the 'Kiruna Truck' showed advantages when travelling on an incline, while loaded. On a 14% ramp the speed for the electric truck running up is almost double when compared to a similar diesel truck (Paraszczak et al., 2014b). However, there was a cost associated with the infrastructure, including the complex design of the power supply line and the need for wider cross-sectional profiles in the drifts.

Epiroc, Boliden and ABB announced a joint collaboration to develop the next generation of trucks for UG metalliferous mining with dynamic charging capability (ABB, 2021). Based on the MT42, the collaboration partners are seeking to develop and demonstrate a battery-electric trolley truck system on a test track in the underground Rävliden mine, satellite orebody and extension of the Kristineberg mine, in northern Sweden. The target is to implement full scale electric-trolley systems at the Rävliden mine by 2024.

Figure 3.3 Earlier 'Kiruna Truck' in operation at an underground mine (image courtesy of ABB).

3.4. 'Small (On-road)' Trucks – Germany's E-Highway (ELISA)

Beside dynamic charging for off-road (i.e., mining) application, there are several projects underway to explore dynamic charging for on-road/highway application. ELISA ('**EL**ektrifizierter, **I**nnovativer **S**chwerverkehr auf **A**utobahnen' = 'electrified, innovative road freight transport on motorways'), is one such project that has been funded by the German government (Linke et al., 2022). First stage of the pilot project involved constructing a 5 km length test track along the A5 motorway between Frankfurt am Main and Darmstadt (in both directions). Construction commenced in 2018, with the test track ready for operation in May 2019 (Autobahn, n.d.).

This involved the installation of the electrical infrastructure and the overhead conductors from Siemens Mobility. This included two 1 MVA 20kV AC/670 V DC rectifier substations, 223 poles along the 5 km test track and further 6 poles in the middle strip (Giebel, 2019).

Since the test track has become operational in 2019, hybrid trucks are now operating on the electric highway several times a day and use dynamic charging along the length of the 5 km test track. The project initially commenced with five Scania R450 hybrid trucks in the fleet, but since then additional seven trucks have been added to the fleet. The trucks are hybrid in the sense that it consists of a 450 HP diesel engine, either 18.5 or 74 kWh battery installed onboard, and the pantograph system from Siemens Mobility. In total, the truck fleet has logged about 2 million km of travel, with 5-10% of the travel being on the electrified highway section. This will allow comprehensive evaluation of the dynamic charging in a real-world application, including how the electric highway can be used for short-haul freight transport (Hanesch et al., 2022).

Figure 3.4 One of the Scania R450 hybrid trucks using the ELISA test track in Germany (image courtesy of Siemens Mobility).

4. Roadmap and Use Cases

A high-level roadmap for the DCI subgroup is presented in Figure 4.1, and this corresponds to the use cases that will be considered in this white paper. Use Case #1 represents the current state of the art technology, and this is the starting point for the discussion in this white paper. As Figure 4.1 illustrates, we anticipate the industry will continue to explore the different use cases in a parallel manner, each with increasing level of complexity. Therefore, it is anticipated that elements of Use Cases #2 to #4 will form the industry's 'future state' as the technology continues to develop.

The use cases presented in this white paper have been developed with the 'Large' and 'Medium' truck category in mind. But once there's increased participation from OEMs of the other truck categories, the use cases will be reviewed – to ensure that any specific use cases from those truck categories are captured and incorporated into the roadmap.

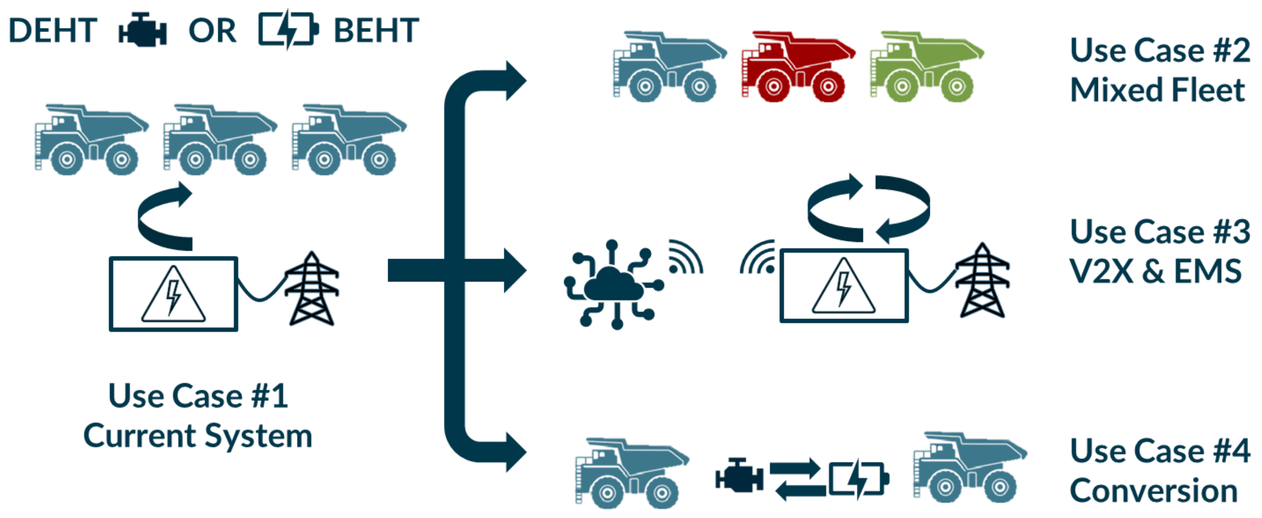

Figure 4.1 High level roadmap for the DCI subgroup's activities.

We also highlight that the lessons learnt, and best practices developed while deploying other technologically complex systems, such as automation, should be leveraged when implementing the use cases. Therefore, topics such as operational readiness and change management will likely be considered by a mine site when implementing a dynamic charging system.

4.1. Use Case #1 – Current System

Use Case #1 represents the current implementation of a dynamic charging systems such as trolley assist, with example implementations described in Section 3. At a high-level, Use Case #1 involves:

- **Haul trucks are in their original configuration.** That is, as built by the OEM, either as a DEHT or a BEHT. It hasn't been converted – for example by, removing the engine and retrofitting a DEHT with batteries and other components, to turn it into a BEHT.
- **The dynamic charging system is used by a haul truck fleet with the same OEM and model.**
    - Even if the site has a haul truck fleet consisting of two (or more) different haul truck models from the same OEM, only one of the models will be using the dynamic charging system. The other haul truck fleet(s) won't be using the dynamic charging system.
    - Therefore, it is only necessary to consider one traction bus voltage. Thus, the electrical conductor voltage has been designed to match the haul truck's traction bus voltage.
- **Unidirectional power flow to the haul trucks.** The haul truck only 'consumes' the energy from the dynamic charging. While the haul truck can generate energy through regenerative braking, any excess energy does not go back into the mine site's grid.

While the haul trucks may be equipped with a wireless communication device (e.g., Wi-Fi or LTE), it does not communicate with the electrical infrastructure systems. For example, it does not provide the input to change the electrical conductor voltage at the rectifier substation.

4.2. Use Case #2 – Mixed Fleet

Use Case #2 is a modification of Use Case #1, where the dynamic charging system is used by a mixed fleet. The 'mixed' nature of Use Case #2 could arise from:

- BEHTs and DEHTs using the dynamic charging system.
- Two (or more) different haul truck models from the same OEM using the dynamic charging system.
- Two (or more) different haul truck models from different OEMs using the dynamic charging system.

For Use Case #2, ideally the traction bus voltage and electrical interface parameters across the mixed fleet will be similar or compatible.

However, if there is a significant difference, then the electrical system on-board the haul truck will need to be capable of performing the DC/DC voltage conversion. As outlined in Section 8.1, potentially the DCI needs to be designed to perform the DC/DC voltage conversion. Furthermore, the electrical infrastructure will be designed for the highest traction voltage requirements, along with the highest current demand.

4.3. Use Case #3 – V2X / Interaction with EMS

Use Case #3 represents an extension of the current state-of-the-art for dynamic charging system by enabling integration between the haul truck and the charging system (such as with the energy management system, EMS).

Additionally, this use case envisages V2X (vehicle-to-everything) capability. For example, V2G (vehicle-to-grid) where the haul truck provides electrical power back to the mine site's grid, or V2V (vehicle-to-vehicle) where the regenerative braking from one haul truck is transferred to the other haul trucks connected to the dynamic charging. As explained elsewhere in the white paper (Section 6.1.4), the group recognizes that such functionality is a future requirement. There is no firm timeline yet on when such functionality will be required.

4.4. Use Case #4 – Retrofit/Convert Existing Machines

Use Case #4 reflects the increasing interest in converting existing DEHTs for BEHT operation. This is given that:

- Transitioning the fleet to BEHTs will take time, given production lead times.
- Additionally, there are still significant number of DEHTs with sufficient life remaining. Therefore, the question of what to do with the existing fleet remains.

At a high level, this involves removing the diesel engine from the DEHT and retrofitting with batteries and other components necessary for BEHT operation. This white paper considers this as a separate use case, as the group acknowledges the engineering development required. Separately, the business case for undertaking the conversion needs to be assessed, which is beyond the scope of this paper. Being a conversion, not all the functionalities outlined in this white paper may be possible, therefore new requirements may need to be evaluated and added to a future version of the white paper or the guidelines.

5. System Diagram

Figure 5.1 illustrates the system diagram for a generic dynamic charging solution. To ensure that the white paper describes a general dynamic charging solution, the white paper refers to the systems and modules as illustrated in Figure 5.1. For example, it refers to a ‘Power Connector’ (i.e., a generic term), rather than a ‘pantograph’ (i.e., a specific instance). We also note that the system diagram in Figure 5.1 has been put together with the ‘Large’ and ‘Medium’ truck categories in mind. But as the requirements from the ‘Small (UG)’ and ‘Small (On-road)’ truck categories are incorporated, there will most likely be further modifications to the system diagram to reflect this.

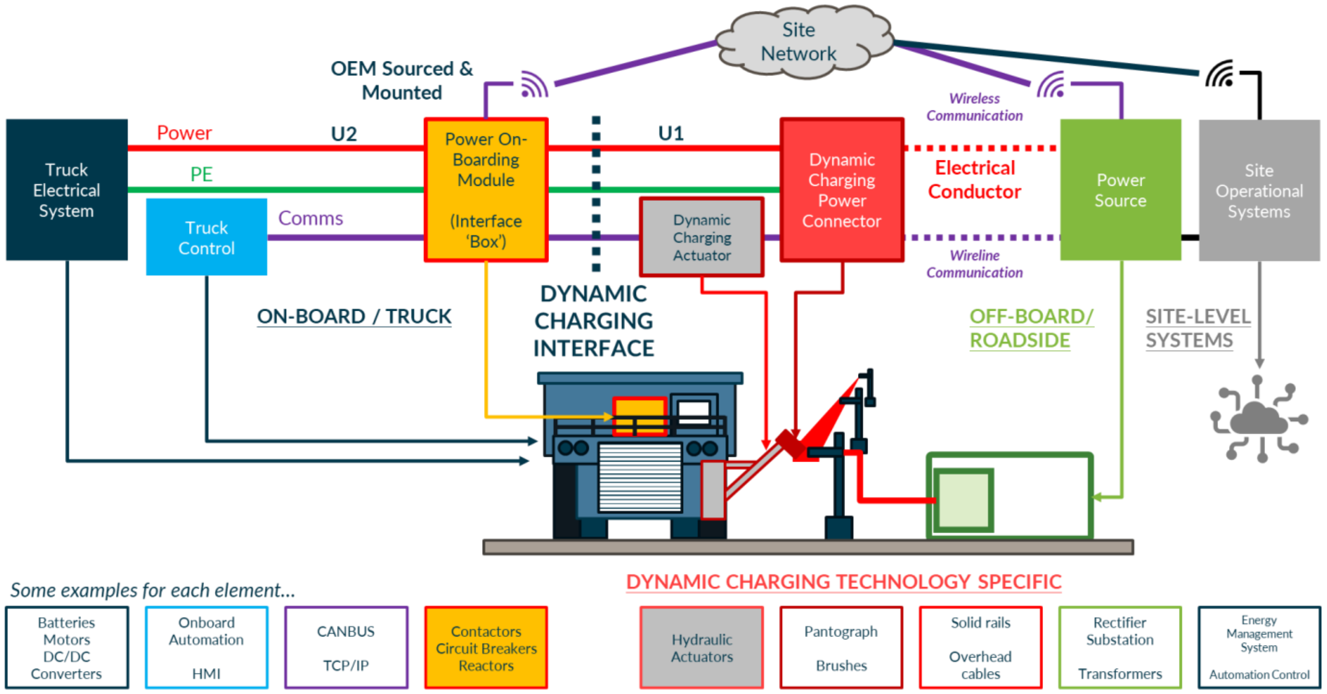

Figure 5.1 Dynamic charging system diagram. In the bottom boxes, examples for each element are listed.

The **Dynamic Charging Interface** is defined to be the point between the **Power Connector** and the **Power On-Boarding Module** on the truck (i.e., the ‘Interface Box’), which may contain components such as contactors, circuit breakers and reactors. We emphasize that this white paper is focusing on the interface and not the design or system on either side of the interface.

- The Power On-Boarding Module connects and transfers the electrical power to the **Truck Electrical System,** which consist of other systems such as the DC/DC converters, batteries, and traction system (inverters, motors). In terms of the data and communication, the Power On-Boarding Module connects to the **Truck Control System.** These are designed by the haul truck OEM.
- Electrical power is drawn from the **Electrical Conductor** (overhead catenary or side rail) by the **Dynamic Charging Power Connector.** This could be the pantograph (traditional trolley) or the electric pick-up (side rail mounted). The Power Connector is mechanically controlled by the **Dynamic Charging Actuator** – which receives the command from the Power On-Boarding Module.

- **Power Source** consists of the mine site's electrical reticulation and the charging infrastructure such as the rectifier substation. Given that this is a 'closed environment', the mine owner is acting as the Charge Point Operator (CPO).
- Elements of the Power Source interfaces with the **Site Operational Systems,** such as the EMS that will control the electrical power available for propulsion and/or charging, and the FMS that will dispatch trucks for charging. Additionally with the operation of autonomous haul trucks, it will also need to interface with fleet automation system.
- As Figure 5.1 illustrates, the communication to/from the Power On-Boarding Module may be performed through wireless (e.g., Wi-Fi or LTE) or wireline (e.g., PLC) communication technologies. While wireless technology may be preferred, the white paper considers all possible options.

Table 5.1 outlines the connections at the DCI, with the implementation details provided in Section 6.1.

Name (short)	Name (long)	Group	Comments
DC+	Power (+)	Power	Per Voltage and current ratings in Section 7.
DC-	Power (-)	Power	Per Voltage and current ratings in Section 7.
PE	Protective earth	Earth	4-GA
DC+ (24V)	24V power (+)	Comms	+24 Vdc
DC- (24V)	24V power (-)	Comms	+0 Vdc
Keyswitch	Machine key status	Comms	+24 Vdc
Control messages	Control messaging	Comms	See Section 6.1.7

Table 5.1 Dynamic Charging Interface parameters

6. Requirements

The requirements for the DCI are introduced and described in this section. This covers the electrical, mechanical and communication interface between the haul truck and the mine site infrastructure. These requirements are necessary to achieve the objectives as envisaged by the subgroup as outlined in Section 1.4.

Section 6.1 covers the requirements that are common across all the truck class sizes and mining applications, while the remaining sections in the document addresses the requirements specific for a particular truck class size. Section 2.1 explains the initial focus on the 'Large' truck category, combined with the relative emissions levels from this class of machines. But the intention is to expand this section in a future version of the white paper to other truck class sizes and mining applications.

6.1. General Requirements

6.1.1. Electrical Safety

The DCI, along with the Power On-Boarding Module and the Dynamic Charging Power Connector, must be designed and manufactured to meet the electrical safety requirements. This includes, but it is not limited to, arc flash, lighting, insulation level, short-circuit withstand capability, ground fault protection and earthing.

Given the global nature of the mining industry, electrical safety legislation and standards differs between countries (and even between states within a country). Therefore, the DCI must adhere to the electrical safety legislation and standards for the jurisdiction in which the system will be deployed.

Australia

For example, from an Australian mining operations and maintenance perspective, this includes, but it is not limited to:

- AS 1768 *Lightning Protection.*
- AS/NZS 3000 *Electrical Installations (known as the Australian/New Zealand Wiring Rules).*
- AS/NZS 3007 *Electrical equipment in mines and quarries—Surface installations and associated processing plant.*
- AS/NZS 4024 *Safety of machinery series, including Part 2901: Electrical equipment of machines - Requirements for equipment for voltages above 1000 V AC or 1500 V DC and not exceeding 36 kV.*
- AS/NZS 4871.1 *Electrical equipment for mines and quarries – General requirements*
- AS/NZS 4871.5 *Electrical equipment for mines and quarries – Battery powered electrical mobile machines.*
- AS/NZS 4871.6 *Electrical equipment for mines and quarries – Diesel powered machinery and ancillary equipment.*

While the Power Source (i.e., mine site's electrical infrastructure) is beyond the scope of this white paper, we highlight that AS/NZS 2067 *Substations and high voltage installations exceeding 1 kV a.c.* should be consulted.

Also, given that this is an emerging area for the mining industry, it is beneficial to look at adjacent sectors with substantial experience (e.g., railways) for guidance and best practices. For example:

- AS 7530 *Electrical Systems*

It is important to note that some jurisdictions (for example Australia) require high voltage apparatus to be earthed as well as isolated as part of any isolation requiring access to electrical equipment. This may necessitate the installation of earth switches, interlocking, as well as live line indication, to allow for maintenance access to the Power On-Boarding Module, and therefore the DCI. Safe access for pedestrians in relation to non-isolated and earthed, high voltage dynamic interface equipment also requires consideration.

United States of America

- CFR Title 30. Chapter I, Subchapter B, Part 18: Electric Motor-Driven Mine Equipment and Accessories (Testing, Evaluation, and Approval of Mining Products)
- CFR Title 30. Chapter I, Subchapter K, Part 56, Subpart K: Electricity (Safety and Health Standards – Surface Metal and Nonmetal Mines)
- CFR Title 30. Chapter I, Subchapter K, Part 56, Subpart C: Fire Prevention and Control (Safety and Health Standards – Surface Metal and Nonmetal Mines)
- CFR Title 30. Chapter I, Subchapter O, Part 75, Subpart T: Diesel Powered Equipment (Coal Mine Safety and Health)
- CFR Title 30. Chapter I, Subchapter O, Part 77, Subpart F: Electrical Equipment – General (Coal Mine Safety and Health)

Canada

- R.R.O. 1990, Reg. 854: MINES AND MINING PLANTS under Occupational Health and Safety Act, R.S.O. 1990, c. O.1
- CSA C22.2 No. 0-20 – General requirements — Canadian Electrical Code, Part II
- C22.2 NO. 281.1-12 (R2017) (Standard for safety for personnel protection systems for electric vehicle (EV) supply circuits: General requirements (Tri-national standard, with UL 2231-1 and NMX-J-668/1-ANCE))
- Ontario Electrical Safety Code (28th Edition)
- CSA M421 – Use of Electricity in Mines

South Africa

- Mine Health and Safety Act, 1996
- Occupational Health and Safety Act, 1993
- Electricity Regulation Act, 2006

OEM and International Standards

From an OEMs design perspective, this includes, but is not limited to:

- IEC 60204-1 *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*
- IEC 60204-11 *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.*
- ISO 14990-1 *Earth-moving machinery — Electrical safety of machines utilizing electric drives and related components and systems — Part 1: General requirements.*

- 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.*
- 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.*
- AS/NZS 4024.1204 *Safety of machinery - Electrical equipment of machines - Part 1204: General requirements.*

6.1.2. Functional Safety

The interface must be designed and manufactured to achieve the relevant functional safety standards, such as:

- ISO 13849 *Safety of machinery — Safety-related parts of control systems*
- ISO 19014 *Earth-moving machinery — Functional safety*
- IEC 61508 *Functional safety of electrical/electronic/programmable electronic safety-related systems.*

This is a crucial requirement given the potential risk for fatalities or damage to property and equipment from normal operation of the dynamic charging (e.g., electrocution or crush injuries from mechanical actuation). Therefore, functional safety standards must be applied so that the DCI can be operated in a manner to meet a broadly acceptable level of risk.

This also extends to the mechanical means of actuating the Dynamic Charging Power Connector. For example, raising and lowering of the pantographs in a trolley assist system, or extending and retracting the electrical pick up in a side rail mounted system. The white paper recommends the Dynamic Charging Actuator is controlled using hydraulics. This provides a separate system for isolating and de-energization. That is, if there is an issue with the Truck Electrical System and the haul truck needs to be disconnected from the electrical conductors, then the truck's hydraulics or even an external source can be used to achieve this. This will significantly improve the SIL rating.

6.1.3. Hardware Interoperability

Along with safety, interoperability is another key objective for the subgroup, as mentioned in Section 1.4.

The interface hardware shall be designed and manufactured with the following requirements to achieve interoperability at the hardware level:

- Power cables to use glanded entry or terminal blocks, as described in Section 8.2.2.
- Use the common connector types, as encountered in the individual truck class sizes. For example, in the 'Large' and 'Medium' truck class sizes we recommended using the 12-position varieties of either the Deutsch® DT series or Tyco® Ampseal 16 series connectors for the communication connection.
- Adopting common pin definitions for the interface. This will allow the same Dynamic Charging Power Connector to connect onto any OEM truck without any additional modification.

Additionally, the Power On-Boarding Module, on which the DCI is located, may be modular (i.e., have sub-modules). This offers number of advantages for the dynamic charging system, including the ability of the hardware to be retrofitted to existing trucks (Use Case #4) and the ease of servicing and repairs.

6.1.4. Electrical Power Transfer

Electrical power transfer between the Dynamic Charging Power Connector and the Power On-Boarding Module is one of the primary functions of the DCI. The interface must be designed and rated, such that for DEHT it can be propelled, while for the BEHT it can be simultaneously charged and propelled.

Use Case #1 captures the current state-of-the-art dynamic charging technology. The power is transferred from the Power Source to the Truck Electrical System (e.g., wheel motors and/or batteries) through the DCI. The white paper sees that in the immediate timeframe this will be the case, with the power flowing in only one direction. But to future-proof the design, some (but not all) stakeholders see that it may be useful for the DCI to be designed with the bi-directional power transfer capability in mind.

Looking ahead, some stakeholders see that DCI may need to support the future functionalities as mentioned below. Such functionalities are at an early conceptual stage, and therefore it isn't a current requirement for the DCI. The white paper is highlighting it now, so that it could be considered in a future version of the white paper.

Future Works – Bi-Directional Power Transfer / V2X

There is interest for the interface to support bi-directional power flow so that a V2G solution can be implemented involving BEHTs. For mining operations, there is interest with V2G given the potential benefits. This includes role it could play in providing grid stability. But equally if it isn't managed properly, lead to grid instability. This would be crucial when an entire mine site converts to BEHT operation that relies on renewable power generation to support the haul truck fleet. Furthermore, this provides an additional energy pathway for the energy generated by regenerative braking, besides charging the on-board batteries (in a BEHT) or dissipating it as heat.

Future Works – Dynamic and Static Charging through the DCI

The DCI should be designed so that it can support both dynamic and stationary charging operation through the single interface. For example, the Power Connector device is suitably engineered and designed so that it can provide a common interface for dynamic charging (while the haul truck is in motion) and stationary charging (when the haul truck has stopped, e.g., for shift change). This will simplify the electrical system on-board the haul truck. Such functionality may require the power transfer to be derated, and this would be controlled by the Truck Control System.

6.1.5. Line Harmonics

When designing the interface, consideration shall be given to minimize the line harmonics, that could cause interference to other trucks that are connected on the conductor, or to the Power Source. Understanding that for DC systems the fundamental frequency is 0 Hz and by strict definition harmonics are not present, harmonics here refers to the voltage and/or current oscillations, much like in an AC system.

6.1.6. Manual or Autonomous Mode of Operation

The DCI functionality must be identical regardless of whether the haul truck is being operated in a manual mode of operation (human operator in the haul truck's cabin) or in an autonomous mode of operation (e.g., remotely from an operating center).

This requirement recognizes that the haul trucks in the 'Large' and 'Medium' category are used on mine sites that may have implemented autonomous mining operations. Therefore, the dynamic charging functionality must be the identical regardless of whether the truck is being operated manually or autonomously.

Furthermore, in such an autonomous haul truck the DCI must connect to the truck's automation system – to deploy or retract the Dynamic Charging Power Connector. Given this connection and interaction, impact to the truck's autonomous system is highlighted, along with any future safety considerations. This white paper highlights that this topic requires further consideration and will be a topic for future work by the subgroup.

6.1.7. Interface to Dynamic Charging Actuator

Another functionality of the DCI is to provide the connection between the Truck Control System and the Dynamic Charging Actuator, thereby allowing the data to be exchanged in a bi-directional manner. The white paper defines the data exchange from the DCI point-of-view.

- Send – Data originates from the Truck Control System. The DCI sends it to the Dynamic Charging Actuator, to control the Dynamic Power Connector.
- Receive – Data is received from the Dynamic Charging Actuator. The DCI transfers it to the Truck Control System, providing the necessary status of the Dynamic Charging Power Connector.

The bi-directional exchange of data is necessary as it allows feedback to either the operators in a manually operated haul truck[5], or to the automation system in an autonomous haul truck, so that the dynamic charging system can be operated safely and effectively.

As a minimum, there shall be a universal/common data set that will be exchanged across the interface, as described in Table 6.1.

Name	Type	Purpose
Engage	Send	Command to the Dynamic Charging Actuator, so that the Dynamic Charging Power Connector connects to the electrical conductor.
Disengage	Send	Command to the Dynamic Charging Actuator, so that the Dynamic Charging Power Connector retracts from the electrical conductor.
Rapid disengage	Send	Command to the Dynamic Charging Actuator, so that the Dynamic Charging Power Connector retracts from the electrical conductor, but at the highest possible rate.

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[5] In a manually operated truck, such systems are commonly known as 'Operator Assist.'

Ready to Engage	Receive	Dynamic Charging Power Connector status – ready to connect to the electrical conductor.
Storage	Receive	Dynamic Charging Power Connector status – it has been stowed away.
Line power	Receive	Dynamic Charging Power Connector status – connected to the electrical conductor and there is line voltage.
Fault status	Receive	Fault status of the Dynamic Charging Actuator.
Actuator status	Receive	Dynamic Charging Actuator status.

Table 6.1 Data set for control interface

At the physical layer, the connection between the DCI and the Dynamic Charging Actuator shall use an existing standard – such as CAN (SAE J1939) or Ethernet.

6.1.8. Emergency Shutdown (Dynamic Charging System)

In addition to the exchange of data as described in Section 6.1.7, the DCI must also provide a separate command or signal for the emergency shutdown of the dynamic charging system.

- The emergency shutdown command does not otherwise impact the haul truck's propulsion, braking, steering, control, or other systems.
- As described in Section 0, as the truck can operate either manually or autonomously, the command for the emergency shutdown must be capable of being initiated either by the operator or the automation system.
- When triggered, this will quickly disconnect the Dynamic Charging Power Connector and de-energize and isolate the on-board elements of the dynamic charging system. This command could also be sent to the off-board systems, which could then determine the appropriate action, including isolation and de-energization of the off-board systems.
- The 'rapid disengage' message may also be used to control the Dynamic Charging Actuator and retract the Dynamic Charging Power Connector.

As this functionality is integral to the onboard safety system, the interface must meet the Functional Safety requirements.

6.1.9. Power Connector Connect / Disconnect

DCI hardware must allow the Dynamic Charging Power Connector to connect and disconnect safely, while minimizing the impact to the haul truck's speed.

6.1.10. Communication with Site Operational Systems

While the haul trucks are equipped with communication systems such as Wi-Fi and LTE for telemetry or autonomous operation, this isn't used to provide feedback to the Power Source. Currently the DCI draws electrical power from the electrical conductors, as determined by the Truck Control System and independent of the other haul trucks connected to the dynamic charging system.

Looking ahead, the DCI will be supporting additional functionalities, some of which have been proposed and highlighted in this white paper. This is the intent of Use Case #3, where the DCI becomes integrated with the Site Operational Systems and interacts with the different digital systems that are necessary for the additional functionalities.

<u>Future Works – 'Smart' power consumption (integration with EMS and FMS)</u>

Use Case #3 envisages communication between the haul truck and the charging system (such as with the EMS) will be necessary[6]. This will allow the haul truck to control the power drawn through the dynamic charging depending on the operational conditions. For example:

- If there is an issue with the power generation, the EMS can request the haul truck to limit its power consumption or in extreme circumstances, for the haul truck to disconnect from dynamic charging.
- The FMS can determine what fraction of the power is used for charging vs propulsion, to optimize productivity and reliability. This requires connectivity between the haul truck and the FMS to ensure that the plan is updated as the mining operation progresses through the shift.
- The information transmitted to the FMS and EMS about the actual power consumption is important to 'close the loop' and optimize the remaining power available in the trolley line.
- Energize the rail/conductor only when the haul truck is connected and requires dynamic charging.

The DCI will play a role in that feedback loop by providing the connectivity with the various Site Operational Systems.

Realizing such capability will require alignment with ISO 23725 *Autonomous System and Fleet Management System Interoperability*, that is currently under development. This will be to include the DCI in the definition of open autonomy standard in mining.

To enable this feedback, the interface will also include external communication capability. Options might include using existing wireless communication technologies (e.g., Wi-Fi or LTE). However, other technologies such as PLC may also be considered (as suggested in Figure 5.1). The decision for the technology must be taken after requirements to which systems to interface is clarified. Furthermore, the limitations of the communication technologies needs be considered, such as its reliability and range.

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[6] One of the Mining Taskforce's five workstreams is to explore the communication protocol necessary for this application.

7. Electrical Interface Parameters

This Section captures the proposed electrical parameters for the DCI based on some of the common traction bus voltages.

As mentioned already, given the initial focus of the subgroup, this Section details the proposed DCI electrical parameters for the 'Large' haul trucks operating with a 2.6 kV DC traction bus system (Section 7.2.1) and a 1.8 kV DC traction bus system (Section 7.2.2). Sections for the DCI electrical parameters for the other truck categories ('Medium', 'Small (UG)' and 'Small (On-road)') are in in this white paper as a placeholder for future work.

7.1. Generic Interface

A generic DCI consists of the following four connection points on the On-Boarding Power Module:

- Power (DC+)
- Power (DC-)
- Protective Earth
- Communication
    - Position 1 – DC+ (24V)
    - Position 2 – DC- (24V)
    - Position 3 – Keyswitch
    - Position 4 – CAN+
    - Position 5 – CAN-
    - Position 6 – CAN shield
    - Positions 7 – Emergency shutdown
    - Positions 8-12 – Reserved / Not used.

7.2. 'Large' Haul Trucks

7.2.1. 2.6 kV DC Traction Bus

Parameter - Nominal	**Unit**	**Min**	**Max**	**Notes**
Power	MW	4.5	8.5	Power is the constraint for the voltage and current.
Voltage (U1)	kV	2.2	2.8	Voltage range while operational
Insulation Voltage	kV		4.5	
DC Ripple	%		5	Voltage and current
Continuous Current	kA	1.6	3.9	Connection (and disconnection) performed done at 0 A
Peak Current	kA		8.0	
Peak Current Duration	s		10	

Parameter –Fault Conditions	Unit	Value	Notes
Impulse Voltage (1.2 / 50 µs)	kV	30	
Over-voltage Category		Category 3	
Peak Short-Circuit Current	kA	100	Based on an example ‘worse case’ scenario as detailed below.

Table 7.1 Dynamic charging interface parameters for haul trucks operating 2.6 kV DC traction bus system.

Short-circuit withstand capability has been determined using an example ‘worse case’ scenario:

- Three BEHTs are connected to the dynamic charging system, with each haul truck drawing the maximum power (8.5 MW). Therefore, the demand will be 25.5 MW.
- The rectifier substation has been designed with 30 MVA capacity.
- The fault occurs near the rectifier substation on the DC side.

Based on this scenario, we estimate that the fault current may be up to 100 kA. If the fault was to be limited by the feeding transformer, we estimate this to be ~75 kA assuming a transformer impedance of 10%. (Rectifier transformers have higher impedance than power transformers). Work by Breugelmans et al. (2014) looking at methods to limit short circuit currents in DC traction networks, using the Brussels Regional Express Network as an example (3 kV DC supply), calculated that fault currents slightly above ~100 kA may be encountered. But to have a better understanding of the fault current that the DCI may encounter, this will require further modelling and calculations. This will be the focus of a future version of the white paper.

7.2.2. 1.8 kV DC Traction Bus

Parameter - Nominal	**Unit**	**Min**	**Max**	**Notes**
Power	MW	4.0	8.0	Power is the constraint for the voltage and current.
Voltage (U1)	kV	1.6	2.0	Voltage range while operational
Insulation Voltage	kV		3.5	
DC Ripple	%		5	Voltage and current
Continuous Current	kA	2.0	5.0	Connection (and disconnection) performed done at 0 A
Peak Current	kA		8.0	
Peak Current Duration	s		10	
Parameter – Fault Conditions	**Unit**	**Value**		**Notes**
Impulse Voltage (1.2 / 50 µs)	kV	30		
Over-voltage Category		Category 3		
Peak Short-Circuit Current	kA	100		Based on an example ‘worse case’ scenario as detailed already.

Table 7.2 Dynamic charging interface parameters for haul trucks operating 1.8 kV DC traction bus system.

7.3. ‘Medium’ Trucks

This section has been reserved for the electrical interface requirements in the ‘Medium’ truck class.

7.4. ‘Small (UG)’ Trucks

This section has been reserved for the electrical interface requirements in the ‘Small (UG)’ truck class.

7.5. ‘Small (On-road)’ Trucks

This section has been reserved for the electrical interface requirements in the ‘Small (On-road)’ truck class.

8. Design Considerations – Power On-Boarding Module

Given that the Power On-Boarding Module plays a central role for the DCI, this white paper proposes that the following design considerations are applied when designing the module. Like Section 7, this Section focuses on the design considerations for a 'Large' and possibly the 'Medium' truck category. Design considerations for 'Small (UG)' and 'Small (On-Road)' truck categories will be considered in a future version of the white paper.

8.1. DC Voltage Conversion Capability

The Power On-Boarding Module shall be designed as either:

- **Type 1** – Where U1 = U2 and no DC conversion takes place inside the Power On-Boarding Module.
- **Type 2A** – Where U1 ≠ U2 and DC conversion takes place inside the Power On-Boarding Module, without galvanic isolation.
- **Type 2B** – Where U1 ≠ U2 and DC conversion takes place inside the Power On-Boarding Module, with galvanic isolation.

Where U1 is the Power Connector voltage and U2 is the Truck Electrical System voltage, as noted on Figure 5.1.

Note – the DC conversion process considered here is specifically inside the Power On-Boarding Module. There may be other DC/DC conversion process that takes place, as part of the existing Truck Electrical System.

The group anticipates that Type 1 will be the most common implementation, where the Power On-Boarding Module doesn't perform any DC conversion. However, there may be situations where a Type 2 Power On-Boarding Module may be needed or beneficial. Use Case #2 envisages a mixed OEM fleet operation, while Use Case #4 envisages converting existing DEHTs for BEHT operations. In such use cases, the voltage for the Truck Electrical System may differ across the mixed fleet. As the conductor voltage is fixed, DC conversion may be required to address difference in the voltage for the Truck Electrical System for the mixed fleet. In such instances, the OEM may decide to implement a Type 2 Power On-Boarding Module.

8.2. 'Large' and 'Medium' Trucks

8.2.1. Operating Conditions

Operating conditions for the Power On-Boarding Module are detailed in Table 8.1. Given the global spread of mining operations, the Power On-Boarding Module is expected to encounter a wide range of operating conditions. Operation beyond the conditions listed in Table 8.1 may result in the Power On-Boarding Module being de-rated.

Parameter	Unit	Values	Notes
Ambient temperature	°C	-40 to +55	This temperature range reflects the global spread of mining operations, which can extend from arctic to arid climates. Additionally, consideration needs to be given for Solar Radiation rating. This will also have an impact on the hardware temperature.
Humidity	%	0 to 100	Without condensation
Altitude	m	0 to 2000	Most operations will be below 2000 m. Therefore, the commonly encountered requirement of 2000 m will be sufficient for most operations.
	m	2000+	However, the white paper recognizes that there are operations where the altitude exceeds 2000m (e.g., in South America).
Ingress Protection	IP	66	As according to IEC 60529 *Degrees of protection provided by enclosures (IP Code)*. Given the harsh mining environment, it should not allow ingress of dust and have level of water ingress protection (IP 66).
	IP	69K	As powerful water jets can be used to clean the haul trucks, higher level of water ingress protection is recommended (IP 69K).
Vibration/Shock		1A	For the sub modules and components as according to IEC 61373 *Railway applications - Rolling stock equipment - Shock and vibration tests.* Enclosure and electric cabinets can be designed according to OEM requirements.
Pollution Degree		3	As according to IEC 60664 *Insulation coordination for equipment within low-voltage* systems. This value reflects the harsh mining environment

Table 8.1 Operating conditions for the Power On-Boarding Module

8.2.2. Power Cable Entry

The power cable between the Power On-Boarding Module will enter and exit the enclosure via suitable size cable glands or terminal blocks. The cable glands must be designed so that the IP rating is maintained.

8.2.3. Active Cooling

With increasing power levels, consideration shall be given for active liquid cooling of the Power On-Boarding Module, in addition to cooling from forced ventilation means.

8.2.4. Insulation Monitoring

As it provides the interface, the Power On-Boarding Module may include an IMD to provide coordination between the on-board and off-board systems.

8.2.5. Equipotential grounding and bonding

Consideration for equipotential bonding must be considered in the Power On-Boarding Module's design. The risks and potential failure modes will vary widely depending on the machine and Power Connector, and whether stationary charging is permitted or not. The white paper recommends that system designers conduct an in-depth review of associated failure modes and mitigation plans depending on the architecture of the various systems. Control actions could be passed through the interface via the use of the *Ready to Engage* and *Rapid Disengage* communication messages.

8.2.6. Wind Loading

While specifying the requirements for the Dynamic Charging Power Connector is currently beyond the scope of this white paper, we note that factors such as wind loading needs to be considered to ensure the mechanical integrity of the Dynamic Charging Power Connector system.

8.3. 'Small (UG)' Trucks

This section has been reserved for the Power On-Boarding Module design considerations in the 'Small (UG)' truck class.

8.4. 'Small (On-road)' Trucks

This section has been reserved for the Power On-Boarding Module design considerations in the 'Small (On-road)' truck class.

9. Implementation Best Practices

This section provides a brief overview of items to be considered when implementing a dynamic charging system. As overhead trolley assist systems already exist in the industry, we use examples from such systems. But the concepts and discussion points from this section are applicable to other dynamic charging technologies. This section is written based on requirements for the 'Large' haul trucks.

We thank Boliden for allowing the material from their guide to be modified and included in this white paper.

9.1. Power System

9.1.1. Electrical Standards

As discussed in Section 6.1.1, the electrical standard for the jurisdiction where the dynamic charging system will be deployed must be adhered. Additionally, as dynamic charging will be used in a mining environment, it must comply with the relevant mining legislation and mining-specific electrical standards. For example, the necessary systems to isolate the energy onboard the haul truck or on the roadside infrastructure.

9.1.2. Earthing and Insulation Monitoring

The trolley assist systems operate in an IT (Isolated-Earth) earthing configuration.

To prevent dangerous touch potential, detection of an earth fault on either the infrastructure or on the connected truck is crucial. An IMD must be used to detect such earth faults – to open the circuit breaker at the rectifier substation.

As mentioned in Section 8.2.4, if the Power On-Boarding Module contains an IMD, this requires coordination with the IMD at the rectifier substation. For example, when the haul truck is connected to the trolley assist system, the IMD on the haul truck is disabled.

An earthing switch must be installed, to allow maintenance on the trolley assist system. This must be sized for the maximum short-circuit current.

9.1.3. Rectifier Substation

To achieve the optimal system, characteristics of the rectifier substation and the design of the overhead trolley should be considered together. As the DEHT and BEHT both operate using DC, the current needs to be rectified from AC. There are two rectifier technologies:

- **Diode rectifiers** are common in the railway sector and for trolley system. To minimize the harmonics, typically 6-pulse diode rectifiers are avoided, and instead 12-pulse rectifiers are typically employed. As the output DC voltage depends on the input AC voltage, significant AC voltage variation (e.g., symptom of a weak network) will impact the trolley system operation. However, if the variation is slow enough, then the use of tap changers on the rectifier transformer may alleviate this issue.
- **Voltage controlled rectifier** allows the output voltage to be controlled and can have a higher output voltage, even when the system is heavy loaded. While it offers better performance, they are more expensive, and the generation of harmonics may require the need for filter installations (additional cost).

Additionally, the rectifier substation shall be equipped with other systems and components for the smooth operation of the trolley assist system. This includes:

- Surge protection to protect the haul trucks and rectifier against any lightning strikes on the contact wires.
- A line test relay is recommended to diagnose the contact wire before closing the DC breaker.
- Communication, control, and monitoring HMI with remote interfaces to enable safe, reliable and smooth operation of the haul trucks connected on system.

If possible, the rectifier substation should be positioned as close to the trolley system, at the middle of the ramp/haul road (to minimize the voltage drop). But this will depend on other factors such as mine planning.

9.2. Roadside Infrastructure

9.2.1. Overhead Structure

Diagram of the overhead structure, along with the main components are illustrated in Figure 9.1, while Figure 9.2 shows what the overhead structure looks like on-site.

- Mast/Pole
- Arm
- Contact wires – the wires that connects to the pantographs when they are raised.
- Messenger wires – the wire above the contact wire to help keeping it on right height level.
- Dropper wires – the wires between the contact wire and the messenger wire (not shown in Figure 9.1).
- Feeder wires – help the system to get a lower resistance if the resistance of the contact wire and dropper wire is too high for the system.
- Earthing wire – a wire/cable either in ground or up in the air connecting all the poles to earth.
- Directional light – a light for helping the operator to keep the course below the contact wires. Alternative methods are also discussed in Section 9.3.2.
- Flood light – a light to lighten up the ramp.

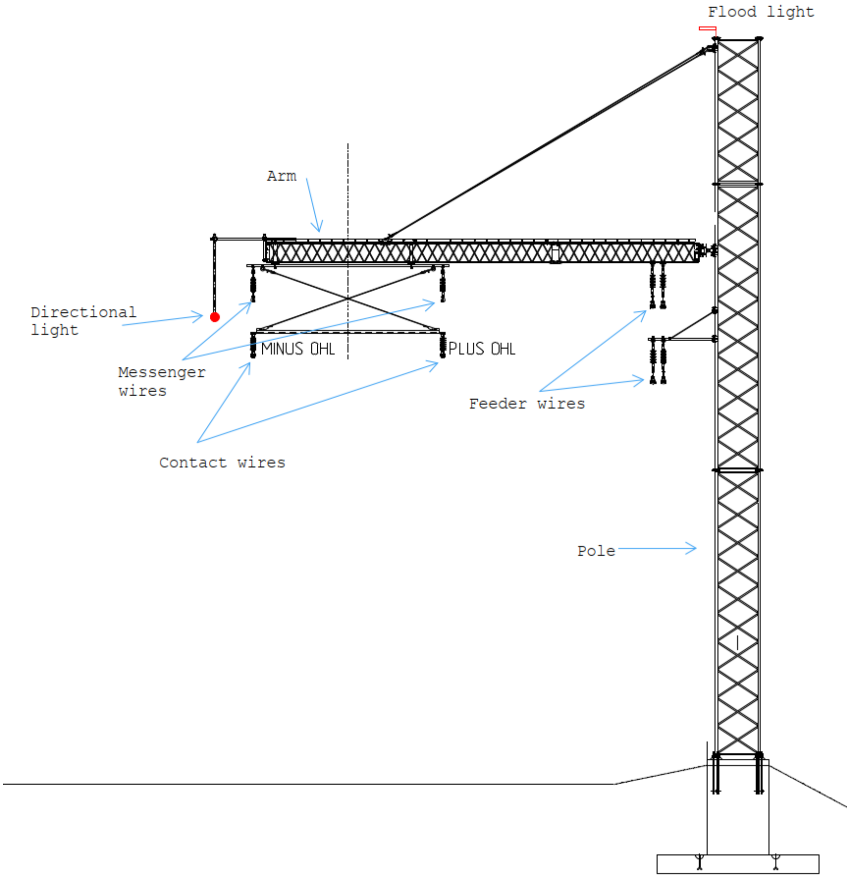

Figure 9.1 Diagram of an overhead structure, along with the key components identified.

Figure 9.2 Overhead structure installed at Aitik mine, taken from a light vehicle travelling along the haul road. Image courtesy of Boliden.

9.2.2. Trolley System Ends

It is recommended that at the either ends of the trolley system, height of the contact wire is at the maximum height of pantograph. This is recommended to minimize the likelihood of damage. For example, if the operator raises the pantograph too early, reducing the likelihood of damage.

9.2.3. Spare Parts

While all measures are taken to minimize the system downtime, end users need to be planned for downtime caused by damage to the equipment. To leverage the existing supply chain network for equipment and components, it is recommended that the trolley system is designed and engineered so that it is aligned to the local adjacent industry sectors such as the railway and utilities – increasing the availability of spare parts.

9.2.4. Support Foundations

Foundations provide stability of the overhead supports and needs to be designed according to the expected loading on the overhead supports and the ground conditions. To minimize time involved in installation, ideally the foundation should be pre-cast. Additionally, if the trolley system is intended to be relocatable, the foundation needs to be designed to allow this to happen – even if this means the initial costs are higher.

9.3. Operation

9.3.1. Load Height Measurement System

An overloaded truck may cause damage to the overhead trolley system – if the height of the load exceeds the height of the contact wires. Based on an assessment, if the risk and likelihood of this incident occurring is unacceptably high, then the end user should consider implementing a monitoring system to warn the operator and/or prevent the truck from driving onto the haul road with the trolley system. Laser scanners (LiDAR) or image processing from a video feed could be used to provide the warning.

9.3.2. Alignment

The truck must be positioned correctly below the contact wires when travelling on the haul road. Depending on the system design, some lateral movement (e.g., up to 1 meter) may be tolerated by the system.

Depending on the capability of the truck, alignment and positioning of the truck may use:

- Manual – Operator uses the position lights or markers to determine the alignment.
- Semi-manual – For example a LiDAR system to detect the contact wire location and provides guidance to the operator for manual correction.
- Automatic or semi-automatic – Using on-board sensors, such as a LiDAR or GPS to automatically steer the truck and maintain alignment.

9.4. Ramp/Haul Road Design

While the white paper focuses on the electrical aspects of dynamic charging, given that the overall system needs to work in a mining environment, we provide a brief overview of the ramp/haul road design elements that should be considered.

- **Entrance point** – For the 'Large' haul trucks with a pantograph, it is recommended that the entrance point is a straight road, to avoid the risk for damage (tear downs). For example, the operator raises the pantograph early and the lateral motion in a curve might damage the system.
- **Length –** Given the fixed cost associated with the infrastructure, the trolley system cost per meter reduces as the ramp/road length increases. This is until the ramp/road is too long such that an addition rectification substation is required.
- **Width –** Many factors need to be considered, including having the ramp/road wide enough to avoid interactions (if there isn't a windrow/bund to segregate the traffic flow). Widening the ramp/road to fit trolley will worsen the business case due to increased waste rock mining required. Furthermore, an additional uphill haul lane may be required, to allow slower mobile equipment, not connected to the dynamic charging, to travel in parallel with the haul trucks connected to the dynamic charging.
- **Protection –** Consideration should be given to protection on the side (a windrow/bund), so that the likelihood of damage is minimized.
- **Gradient –** If the gradient is varying to much there could be some design issues and extra cost for the overhead line system. The problem is when the gradient is changing too much on a short stretch.
- **Curve –** Curves will require the overhead structures to be closer together (which will increase the installation costs). While it depends on the exact model of the haul truck, for a manually operated truck, radius of 150-200 m may be possible. This could be reduced further if the haul truck is operated autonomously. Furthermore, in the 'Medium' haul truck application at VA Erzberg (Section 3.2), smaller radius of 13 m has been achieved.
- **Ground Conditions –** It is crucial that the ground conditions are adequate for the foundations. Otherwise, the cost would increase if additional measures, such as piling is required.
- **Road/Ramp Conditions –** Good conditions are necessary to ensure continuous connection between the pantographs and the contact wires.
- **Blasting –** Depending on the location and mining operation, the risk of damage from blasting (i.e., flyrock) needs to be considered. Damage to the overhead structure will cause downtime, as the damage may need to be inspected and appropriate course of action determined.

10. Next Steps for the DCI Subgroup

The DCI subgroup recognizes that this white paper is the start of the engagement between the mining industry, haul truck and electrical OEMs around dynamic charging and future requirements. The white paper has already identified the future work, some of which will be explored further when the next version of the white paper is released. This includes:

- Mine site's electrical infrastructure, including greater integration between on-board and off-board systems.
- Other truck class sizes, especially the electrical parameters and design considerations for 'Small (UG)' and 'Small (On-road)' truck categories.
- Other equipment type, beyond haul trucks.
- Bi-Directional power transfer (V2X).
- Dynamic and static charging through the DCI hardware.
- 'Smart' power consumption (integration with EMS and FMS).
- Fault current calculations, to determine short-circuit withstand capability.

Additional topics will be captured based on future discussions and engagements.

11. Conclusion

This white paper represents the first iteration in outlining the technical requirements for a DCI on-board a haul truck. Dynamic charging will have a key role as the industry witnesses a transition towards BEHTs, as it allows the haul trucks to both charge its on-board batteries and propel using its motors, while it is in motion, thereby ensuring that it maintains their availability or utilization. Given the expected increase in the dynamic charging systems to be implemented in the future, as part of the electrification trend, it is crucial that dynamic charging and the interface is standardized and allows interoperability. This white paper represents the first towards this goal.

Furthermore, given the rapid pace of technological development in this sector, this white paper has captured some of the 'forward-looking requirements' in anticipation of future developments.

Finally, this white paper also demonstrates that the current state-of-the-art technology has been made possible through the past innovative and pioneering work – including the implementations that have been discussed in Section 3. For the industry to progress with the dynamic charging in a safe and efficient manner, such learnings need to be captured and shared across the sector. This white paper has tried to capture the background information and guideline for implementation – serving as a useful resource for future implementation of dynamic charging systems.

12. Reference

This document was created by the Dynamic Charging Interface subgroup of the Mining Taskforce – a partnership between CharIN and ICMM (International Council on Mining and Metals) to address technical bottlenecks around the interoperability of battery-electric charging systems for zero emission greenhouse gas (GHG) mining vehicles.

The purpose of this effort was to align the industry for a standardized and interoperable DCI for mining applications – thereby increasing safety, promoting alternative solutions, reducing duplication, potential waste of effort and enhancing cost-effectiveness.

Other useful documents exist and will continue to be created and revised in standards bodies. This whitepaper is not intended to be exhaustive or frozen, and documentation will continue to be updated over time.

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