White Paper
of Charging Interface Initiative e.V.

Static Charging Interface for X-MCS

2025-10-28

Charging Interface Initiative (CharIN) e.V.
c/o CharIN Academy GmbH
EUREF-Campus 10-11

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

Contents

ICMM CHARIN

Executive Summary

The mining industry is at a critical juncture in its decarbonization journey. As one of the most energy-intensive and high emissions, primarily due to its reliance on diesel-powered equipment, the industry urgently needs to transition to cleaner, decarbonized operations. Electric vehicles (EVs) and battery-powered machinery are central to this transformation, offering significant environmental benefits and supporting global climate goals. However, the widespread adoption of electric mining equipment hinges on overcoming technical challenges—particularly the development of fast, reliable, and safe charging solutions that support continuous operations.

eXtreme Megawatt Charging System (X-MCS) introduces a breakthrough approach, enabling ultra-fast charging—potentially fully charging large haul trucks in just three minutes. Such rapid charging minimizes downtime, enhances operational efficiency, and makes large-scale electrification more feasible. X-MCS's high power capacity, achieved by increasing voltage to 3,000 volts DC, can deliver up to 12 megawatts or more—supporting not only mining vehicles but also other sectors like rail and marine, thereby fostering broader industry decarbonization and sustainable growth.

This white paper establishes a technical foundation for X-MCS development, detailing hardware specifications, safety standards, and communication protocols. Given the high voltages involved, automated coupling systems will be necessary to ensure safe, reliable, and efficient connections between chargers and vehicles.

The objectives are to identify key technical challenges—such as thermal management, safety, and interoperability—and to develop standardized recommendations that facilitate safe, scalable, and effective high-power charging solutions. Achieving these will require collaboration among mining companies, OEMs, infrastructure providers, and standards bodies to pilot and scale X-MCS.

ICMM and CharIN's collaboration underscores the importance of industry-wide cooperation, sharing expertise, and aligning efforts to accelerate the deployment of high-power, safe, and sustainable charging infrastructure.

1. Introduction

Launched in 2021, the Charge-On-Innovation-Challenge (COIC) is a collaborative initiative founded by ICMM members—BHP, Rio Tinto, and Vale—and championed by fellow industry leaders. Its goal is to accelerate the development and deployment of large-scale electrification and rapid-charging technologies for mining equipment. By harnessing innovative ideas from around the world, COIC addresses the critical challenge of decarbonizing mining operations—an energy-intensive sector responsible for significant greenhouse gas emissions.

Decarbonizing mining is essential to meet global climate targets, but it requires solutions that enable continuous, large-scale electrification without operational disruptions. To this end, COIC fosters innovation in high-power charging systems which aims to support the rapid, safe, and reliable charging of large battery electric haul trucks and other heavy-duty vehicles.

In 2022, submissions from technology innovators now advanced beyond initial conceptual stages, to proof of concepts/trials, demonstrating promising solutions for high-capacity charging. These innovations not only have the potential to revolutionize mining but also contribute indirectly to emerging markets in sectors like marine and rail transportation.

Building on this momentum, in 2023, CharIN was selected as the platform to develop requirements for an interoperable, high-power static charging system capable of transferring more power than current systems. The resulting X-MCS is designed to support large-scale electrification across multiple sectors.

ICMM, through its partnership with CharIN and its Innovation for Cleaner Safer Vehicles (ICSV) initiative, has played a key role in bringing industry stakeholders together. This collaboration aims to ensure that the development of X-MCS aligns with responsible practices and decarbonization goals. Industry partnerships will be essential to overcome technical hurdles, foster innovation, and accelerate the transition to sustainable, zero-emission mining operations.

1.1. Motivation for X-MCS

The motivation for having a new, high power static charging system is to increase the productivity of ultra/large class BEHTs. By charging at higher powers, this reduces 'Operational Delay' due to faster charging, thereby increasing the BEHT's 'Operating Time.' Additionally, this requires quick connection/disconnection between charger and truck. To achieve this objective, the connection must be automatic.

X-MCS belongs to the SCI (Static Charging Interface) group like CCS, MCS and R-MCS. The vehicle is parked while charging, this in contrast to the DCI (Dynamic Charging Interface) where the vehicle is charging in motion respectively while it is driving.

Members of the X-MCS working group within the Mining Task Force[1] started working on this white paper[2] in early 2024. This white paper has been prepared to:

- Outline the basic parameters of a high-power static charging system, thereby providing a basis for a new standard for such charging. This includes:
  - Electrical parameters, including the intended range of operating voltage and current.
  - Functional requirements, emphasizing the importance of features such as scalability, interoperability and autonomous operation.
  - Electrical safety.
  - Hardware requirements, including the two types of connectors based on the present state-of-the-art technology
- Enable the broader industry (mining companies, truck OEMs, electrical hardware suppliers) to plan or carry out development with some assurance of broader industry alignment
- Facilitate the adoption of high-power static charging that could have significant benefits for mine operations and covers a need that is not met by Ruggedized MCS (R-MCS) or dynamic charging solutions. X-MCS is intended to offer higher charging power, to reduce stopping time, when compared to R-MCS and thereby increases productivity. X-MCS offers greater flexibility and likely lower capital investment cost compared to dynamic charging. While there are certainly pros and cons to each system, it is not the intention of this white paper to make such a comparison.

To meet the target set in COIC of charging a BEHT with 400kWh, in 3 minutes, this white paper recommends that the X-MCS needs to be capable of transferring 12 MW of electrical power at 3,000 V DC (i.e., the current is 4,000 A DC). However, lower current values are also suggested as intermediate steps in achieving this goal.

[1] Mining Task force was a partnership between CharIN and ICMM (International Council on Mining and Metals).
[2] In addition to this X-MCS white paper, the Mining Taskforce has prepared other white papers on a ruggedized version of the MCS, known as R-MCS and another on a Dynamic Charging Interface (DCI). The white papers can be downloaded from CharIN under 'Position Papers and Regulation', https://www.charin.global/technology/knowledge-base/

2. X-MCS Requirements

2.1. Fundamental Requirements

The white paper considers the following requirements as being fundamental in the proposed X-MCS system.

- Safety and reliability are the two key requirements. This should be, and must be, at the forefront when making any decision in the development of a new charging interface.
- Haulage productivity should not be significantly compromised when transitioning from Diesel Electric Haul Trucks (DEHTs) to BEHTs. This means that the number of trucks and the payload per haul truck should not vary significantly from the base case involving the DEHTs. In the case of static charging, short charging times are important for the operation of a mine. As such, X-MCS targets higher power energy transfer to minimize charging time.
- The charging system for static charging using the X-MCS interface should be interoperable.

2.2. Charging Voltage and Power Ratings

This guideline must be developed from the beginning. We are entering in a new technology domain where the batteries for electric mobile equipment have capacity in the range of one to several megawatt hours (MWh), voltages approaching 3,000 V DC and charging rates in the order of 10 C (C-Rate). The C-rate of a battery indicates the rate at which it charges or discharges relative to its capacity. A 1C rate means the battery will be fully charged or discharged in one hour. For example, a 2C rate means it charges or discharges in 30 minutes, while a 0.5C rate takes two hours.
Table 3 in this white paper shows the different C-rates.

It is proposed that there are different levels of ratings for the following reasons:
- the onboard converters of many trucks are not rated for 3kV
- many battery management systems (BMS) are not rated for 3kV
- a step-by-step approach is being applied by many charger and truck OEMs to ensure charging works a lower currents and voltages before attempting to charge at higher values.

2.2.1. Charging and Coupling Device Power

This requirement must be based on, and then aligned to, IEC 61851.

It is proposed to have different rating for the coupling device and charging process. This is because:

1. Charging may occur at two voltage levels, nominally 1.5kV and 3kV, whereas it is desirable to standardize on a single plug voltage. A single plug voltage reduces the number of variants, and the incremental cost associated with the higher voltage is expected to be low.
2. A slightly reduced upper voltage of 2.6kV (as opposed to 3kV) would meet the ratings of semiconductors commonly available for trucks and chargers making it a sensible limit for charging power. A coupling device does not have this constraint, so it is convenient to select a round number which is also a standard voltage in railways.

The nominal maximum values of power for the coupling device are defined by levels so that higher levels can be selected as technologies become available to allow such higher powers. These values are given in Table 1.

Table 1 Nominal maximum values of charging power for the coupling device

Level	Current (kA)	Voltage (kV)	Power (MW)
1	2	3	6
2	4	3	12
3	5	3	15

2.2.2. Charging Power

The realistic power used for charging is expected to be lower and typical values are shown in Table 2.

Table 2 Realistic values of charging power by case

Case	Current (kA)	Voltage (kV)	Power (MW)
a	2.3	2.6	6
b	3.1	2.6	8
c	4.6	2.6	12

Note that the stated power would only be delivered at maximum voltage. For lower voltages the power would be constrained by the maximum current and so the charging level should be selected with this in mind. For example, should 6 MW of power be required at 1.2 kV (the presumed state of charge of a 1.5 kV battery) the required current would be 5kA which would require a level 3 coupling device.

2.3. System Description for X-MCS

The system should be viewed holistically to ensure all the components operate together in an interoperable manner. That is, from the mobile equipment battery via the Power Distribution Unit (PDU) to the Automatic Coupling Device (ACD) to the Electric Vehicle Supply Equipment (EVSE). Figure 1 illustrates the main components of the X-MCS charging system:

- Battery: Battery with liquid cooled Thermal Management System (TMS), Battery Management System (BMS) and fuse-based DC protection
- PDU: Power Distribution Unit (DC distribution in and out & protection)
- LCU: Liquid Cooling Unit to dissipate the heat generated during the X-MCS charging
- ACD: Automated Coupling Device (lateral arm, pantograph or plug socket system)
- EVSE: Electric Vehicle Supply Equipment in DC current control (battery charger)

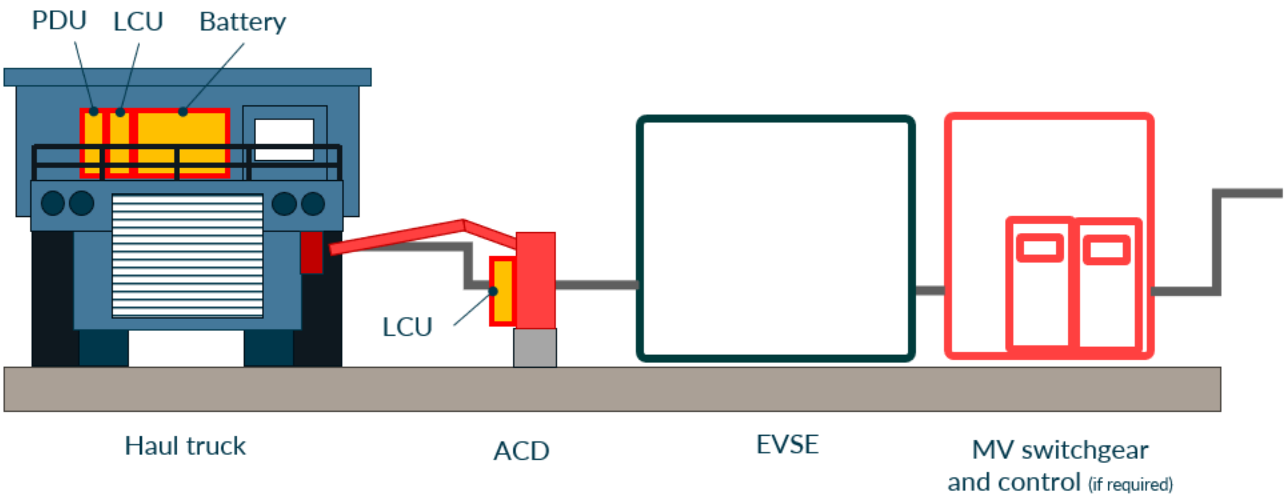


Figure 1 Components of a X-MCS

2.4. Battery and Charging Current Requirements

The battery must be able to handle high C-rates, as dictated by the battery chemistry, and a very high cycle life at frequent fast charging.

As per the requirements outlined in COIC[3], charging should be performed every 30 minutes in a 24/7 operation up to 7000 to 8000 hours per year (1 year = 8760 h). So, the duty cycles are up to 16,000 cycles in one year. As requested by the COIC, the 400 kWh energy demand of the large haul truck should be recharged in 3 minutes. In a linear calculation this leads to 400 kWh x 60 / (3 h) = 8,000 kW of charging power.

Table 3 demonstrates the C-rate, the value of the DC current and the charging time in dependency of the battery capacity, the given energy demand (400 kWh) and the charging power. Note that in estimating the charging time vs charging power allowed by battery C-rate, the converter efficiency & total system losses are not considered. Therefore, the charging times listed below in Table 3 are based on an ideal situation.

[3] This is the 'profile X' that was considered as part of the COIC.

Table 3 Charging time overview for different C-rates

Battery Capacity	Recharge Energy	EVSE power	Charging C-rate	DC current @ 3000 V DC	Charging time in min & sec
1MWh	400 kWh	1 MW	1 C	333 A	24 min
1MWh	400 kWh	5 MW	5 C	1,666 A	4 min 48 sec
1 MWh	400 kWh	8 MW	8 C	2,666 A	3 min 0 sec
1 MWh	400 kWh	10 MW	10 C	3,333 A	2 min 24 sec
1 MWh	400 kWh	12 MW	12 C	4,000 A	2 min 0 sec
1 MWh	400 kWh	15 MW	15 C	5,000 A	1 min 36 sec

To limit the C-Rate below 10, the battery capacity must be in the range of 1 MWh. Although the charge is only 400 kWh, so only 40 % of the battery capacity is used. It is a tradeoff between battery weight and aging prevention due to the C-Rate being too high.

The actual progress in battery development for high-energy and high-power battery cells is promising to further reduce the overall battery capacity without increasing the aging.

The recommended DC current up in the range of 4,000 A is realistic as many DC apparatuses are already existing and widely used in the railway industry at 3,000 V DC. Converters at megawatt power levels are not seen as a problem because these devices are widely used in others industrial applications like electrolysers, photovoltaics and battery energy storage systems.

For the COIC target with 400kWh energy demand, only 8 to 10 C charging with approx. 8 to 10 MW charger and 4,000 A coupler would fulfill the 3-minute target duration for charging. An exact loading curve is here not considered and would be subject during a proof-of-concept development project.

3. X-MCS Functional and Performance Requirements

3.1. Must Have Requirements

This section details the functional and performance requirements of the X-MCS.

High, Efficient and Scalable Power

X-MCS must be capable of delivering the power as specified by this standard. Ideally, the system must also have a “boost” mode to supply higher power with duty cycle.

As batteries get larger in energy capacity, and as needs for faster charging increases, more power will be needed in the future. X-MCS must be of technology that allows for easy and safe scalability of power. Ideally, the X-MCS can also be deployed as two units in parallel to double the power.

Automatic Operation

Given the extreme power, X-MCS must operate in a fully automatic manner.

Interoperability

Across vehicles, EVSEs, and types of mines.

Ruggedness

Against electrical stresses such as ripple, over voltage, and/or over current.

Against mechanical stresses such as vibration and continuous usage.

Against thermal stresses due to high current or increased resistance of the connector.

The X-MCS must operate normally and safely under the above stresses.

Reliability

Low downtime, low maintenance, long life, high mating cycles, despite continuous and heavy usage.

Positioning

Quick EVSE and truck positioning and quick pairing with certain mating space.

Applications

X-MCS shall work with various types of mine vehicles, as well as mine machinery and equipment. Moreover, X-MCS can be used in other industries requiring high power such as marine and rail.

Efficiency

The coupling device must be of low resistance to save on electricity usage. Moreover, it will produce less heat, which is safer, and increases reliability. If used underground, less heat generation becomes more important.

3.2. Safety Requirements

3.2.1. Key Safety Hazards That Must be Addressed

Safety must have the highest priority in the X-MCS standardization and product design. The following safety related hazards (predominantly electrical) must be addressed developing a future standard for the X-MCS.

- Electric shock due to direct contact
- Electric shock due to indirect contact
- Touch potential and Step potential under fault or machinery failure conditions
- Discharge through stray shunt impedances or shunt impedances deliberately inserted into the circuit e.g. as filters. (Both types of impedance are also known as Y impedances)
- Arc-flash, including arc fault contained equipment and considerations for ensuring personnel are removed from any arc flash boundary.
- Over Temperature
- Crushing and entanglement, with consideration for Functional Safety controls (e.g., moving parts hitting people).

At first instance, these hazards must be controlled through 'hierarchy of control.' Where elimination and substitution cannot be achieved, then engineering controls should be employed. For example:

- To prevent arcing, the connector must employ a "last make, first break" contact sequence for the control pilot. This ensures that power is shut down before the power contacts separate during the sequential power-up and power-down process.
- Sensors monitor temperatures and shut the system off in response to over-current, fault current, or short circuits.

3.2.2. Discussion on Human Touch Safety

Human touch safety of the EVSE has been addressed during the progression of vehicle charging standards as follows from CCS (Combined Charging System) to MCS, R-MCS and X-MCS:

- The CCS for battery electric vehicles (BEVs) allows human touch while charging, because of reduced output voltage (1000 V DC) combined with reduced Y-Capacitance.
- The MCS for BEVs (e.g., electric heavy-duty trucks) allows human touch while charging because of reduced DC output voltage at 1250 V DC level and with limited Y-Capacitance.
- The R-MCS with 1500 V DC output voltage and up to 6 MW charging power and substantial larger Y-Capacitance tolerates human touch in a non-public space by experts wearing special equipment such as HV safety gloves[4]. The energy stored will exceed the values imposed by MCS standard for Safety (IEC17409, IEC61851-23, SAE J1772). Furthermore, there is preference for R-MCS solutions to be automated.

[4] While the industry should strive towards eliminating this scenario, for the time being it is not possible.

- The X-MCS with 3000 V DC output and a large Y-Capacitance cannot tolerate any human touch during charging at present safety regulations. Once the coupling is performed no one shall touch either the truck nor the EVSE (including coupler, cables and EVSE). The driver should remain seated in the vehicle during charging.

For the future system it will need to be checked what measures must be taken so that the operator can leave or onboard the vehicle during charging.

3.3. Communication

In terms of the communication between the BEHT and the EVSE we recommend following as much as possible existing standardized, proven and reliable solutions such as CCS, MCS, R-MCS and Opp Charge (Wi-Fi).

At first instance, the communication between the BEHT and the EVSE should be wireless. Wireless communication connections are already in operation. For example, since 2018, Opp-Charge Systems (Opportunity Charging) has been used for electric bus fleets in public transportation. If needed, as a backup and for reliability, a wired connection should also be considered, such as Ethernet based on ISO 15118 and or CAN.

Several levels of communication for the overall system needs to be considered:

1. communication while approach of vehicle to the charging / parking position for example using RFID/UWB or BLE to indicate a truck is approaching.
2. During the approach the connection between vehicle's BMS and the ACD shall be established. This communication manages the charging process.
3. communication of the ACD / Static Charging Infrastructure (SCI) to the EVSE.
4. communication from EVSE to centralized/remote control center with energy management system and fleet management system

3.4. Recommendations for Operation

The coupling and decoupling time of an X-MCS Charging System should not take longer than 5 to 10 seconds once the BEHT has stopped in the parking position. Once the connection is made the charging process should start right away which means the BMS and the EVSE should communicate wirelessly during the approach. The rationale is not to lose time (several seconds) in exchanging data after making contact.

The tolerances of the parking positions and alignment shall be within a range which trucks can achieve and within the reach of Automatic Coupling Devices. Of course, the parking / charging area should be prepared to keep the tolerances as low as possible.

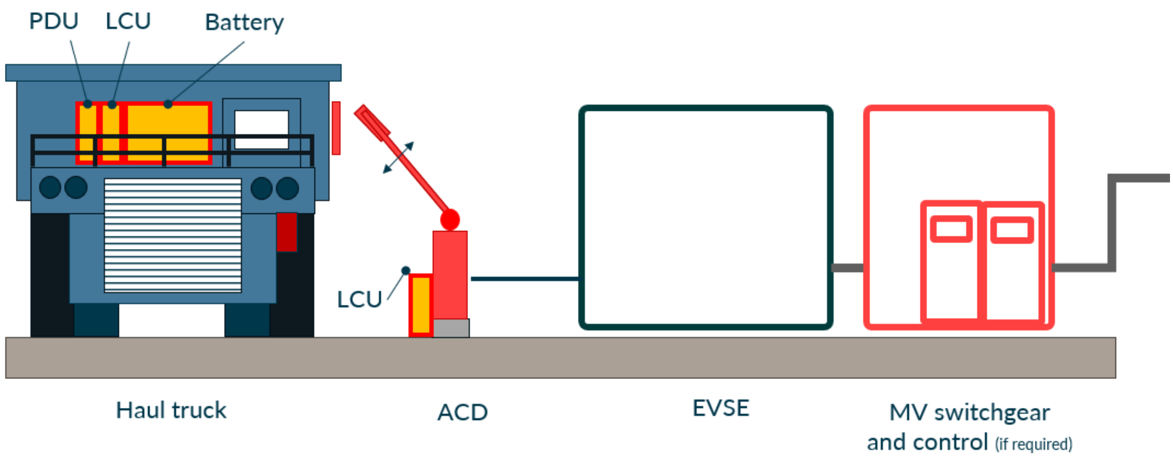
Option: Charging while loading/unloading - moving vehicle – get info from OEM and mining industry – for the time being no charging during loading and unloading, look for a smooth description.

4. Hardware Solutions for the Automatic Coupling Device

The ACD transfers electrical power from the EVSE to the battery via the PDU onboard the mobile equipment. The white paper proposes two types of ACDs based on current state-of-the-art technology:

- **Type A** – Mechanically guided with open contacts
- **Type B** – A pin and socket connector

Type A – Mechanically guided with open contacts. A mechanically guided arrangement with open contacts could look like drawing below in Figure 2. This type of arrangement is based on solutions for opportunity and flash charging of electric busses at terminals or bus stops.



PDU: Power Distribution Unit; LCU: Liquid Cooling Unit; ACD: Automatic Coupling Device; EVSE: Electric Vehicle Supply Equipment

Figure 2 Type A – Mechanically guided with open contacts

A single downward motion of two arms (one positive and the other negative) is all that is required for the connection. The connection head is mechanically guided into position by V-shaped “sockets” on the truck. This has been used in public transportation since 2013 and provides reliable connection without any additional demand on the driver with respect to the parking position. Today, millions of kilometers have been run and millions of connections made using such a guided system.

There is no dependence on laser, infrared, sonar, or other detection systems. This makes the system more robust and reliable in the harsh mining environment. It would be insensitive to dust, rain and snow. At the same time, it allows a certain degree of tolerance in the stopping position of the haul truck.

4.1. Type B – Pin and Socket Connector

A pin and socket connector is illustrated below in Figure 3.

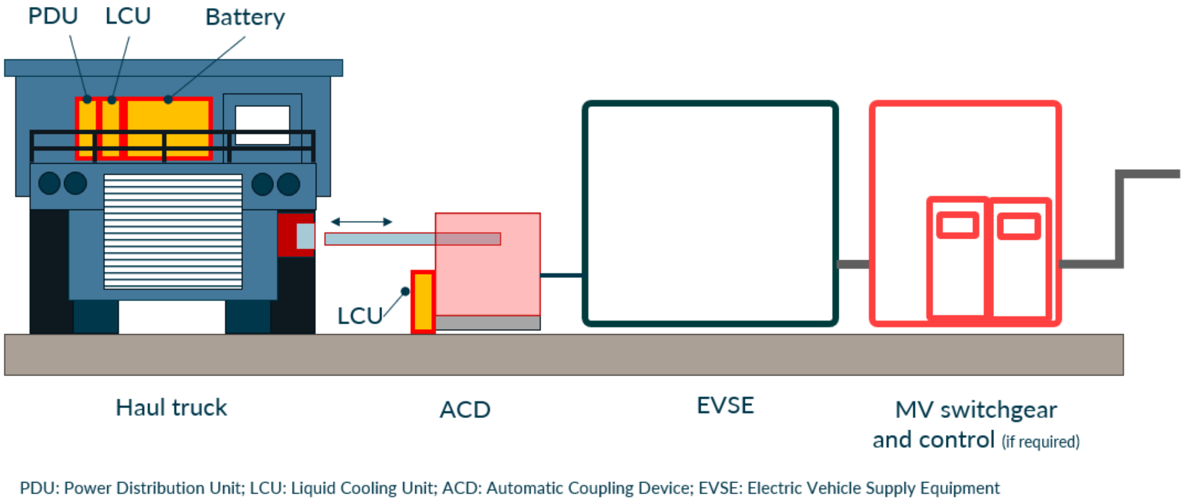


Figure 3 Type B – Pin and Socket Arrangement

High-power pin and socket connectors have already reliably performed tens of thousands of charging sessions in demanding environments. Today a liquid-cooled pin-and-socket connector can deliver 7.5 MW continuously.

The power contacts are circular rings around the pin. This allows the current and heat to flow around evenly, therefore reducing hot spots and reducing thermal stress. Pin and socket connectors meet the IP66 requirements and are IP2X touch protected.

Pin and socket connectors are automatic. A flexible pin is integrated into a platform that wirelessly senses the vehicle's approach and moves it along three axes to align it with the socket. Next, a funnel guides the pin into the socket, compensating for any remaining misalignment.

Pin and socket connectors follow the SAE J3105, 3105/3, IEC61851-23, and EN50696 standards.

These connectors can be scaled up in power and enhanced with additional functional and safety features for the foreseeable future.

4.2. Testing

A testing programme should be developed to ensure safety and reliability of the X-MCS system.

This should cover the following areas

Electrical safety and reliability tests such as

- Continuity of protective earthing
- Insulation resistance
- Insulation withstand
- Short circuit withstand
- Short circuit breaking
- Arc with stand
- Heat run test
- EMC emissions
- EMC immunity

Mechanical safety and reliability tests such as

- Mechanical impact withstand
- Mechanical endurance

Environmental test such as

- Temperature withstand for high and low temperatures
- Dust
- Salt mist
- Ice, rain and snow
- Ingress protection
- Shock and vibration

Functional tests such as

- Communication interface between the truck and ACD
- Communication interfaces between ACD and the EVSE

This list is not intended to be exhaustive but rather a guide as to what would need further development in order to achieve the ultimate goal of having a standard. Furthermore, it is recommended to align the testing requirement with rail and marine industry.

4.3. Provisions for Maintenance, Service or Emergency Purposes

In case of maintenance, service in a workshop or in emergency cases we recommend having an additional charging interface based on CCS or MCS or R-MCS to charge the battery respectively parts or the battery. During service we run on lower power ranges to check the connectors, etc. so interlocking systems could have a different level of safety for trained certified technicians.

5. Conclusion

The X-MCS solution represents the most challenging charging system in the vehicle arena. The high operation voltage does not tolerate any human touch (at present). This white paper is the first step to describe and define the technical basics for an eXtreme Megawatt Charging System (X-MCS).

An important component for moving into the direction of X-MCs is the battery on the truck. Further improvement on power and energy density of battery chemistry is needed to reduce the weight of the battery packs. The other aspect is the robustness of the battery chemistry to cope with charging cycles in the rough environment of a mine site.

This white paper has envisioned already some of the forward-looking requirements in anticipation of the future developments.

This white paper also encourages the readers to look across other sectors in industry and transportation to use components and methods for this new system. Battery trains and battery vessels are for example an area to check on developments and technologies to use and transfer.

Therefore, collaboration, co-creation and later on extensive tests in a proof-of-concept phase are needed from all parties involved: mining industry, Truck OEMs and EVSE OEMs must drive this development together.

6. Annex

6.1. List of Abbreviations

Abbreviations	Definition
CCS	Combined Charging System
EVSE	Electric Vehicle Supply Equipment
ICMM	International Council on Mining and Metals
IEC	International Electrotechnical Commission
MCS	Megawatt Charging System
R-MCS	Ruggedized Megawatt Charging System
AC	Alternating Current
BEHT	Battery Electric Haul Truck
CharIN	Charging Interface Initiative e.V.
DC	Direct Current
DCI	Dynamic Charging Interface
DEHT	Diesel Electric Haul Truck
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
OEM	Original Equipment Manufacturer
SAE	Society of Automotive Engineers
ACD	Automatic Coupling Device
LCU	Liquid Cooling Unit
PDU	Power Distribution Unit

6.2. Reference

This document was created within a subgroup of the Project Mining working group of the CharIN association, in collaboration with the ICMM.

The Project Mining working group is dedicated to accelerating the electrification of mining applications by developing standardized, high-power charging solutions tailored to the operational demands of the mining sector.

This subgroup specifically focuses on defining the technical and functional requirements for an interoperable, automated, and safe high-power static charging system for Battery Electric Haul Trucks (BEHTs) and other heavy-duty mining machinery.

By bringing together CharIN members, ICMM member companies, OEMs, infrastructure providers, and standardization experts, the group fosters innovation, ensures system compatibility, and enables scalable global deployment of electric mining infrastructure.

This collaborative effort contributes to the broader industry goals of decarbonization and sustainable development by advancing reliable and efficient charging technologies for demanding industrial environments.

Special thanks go to all contributors from the participating organizations for their valuable input, dedication, and technical expertise in shaping this foundational document. To name them:

Christian Ebert (Hitachi Energy)

Tariq Kareemulla (ICMM)

Kwan Lee (Rio Tinto)

Sasan Khajavi (Stäubli)

Bruce Warner (Hitachi Energy)

Uwe Hotz (Nyobolt)

Christoph Schlegel (ABB)

Theodore Bohn (Argonne National Laboratory)

Semih Tetik (CharIN)