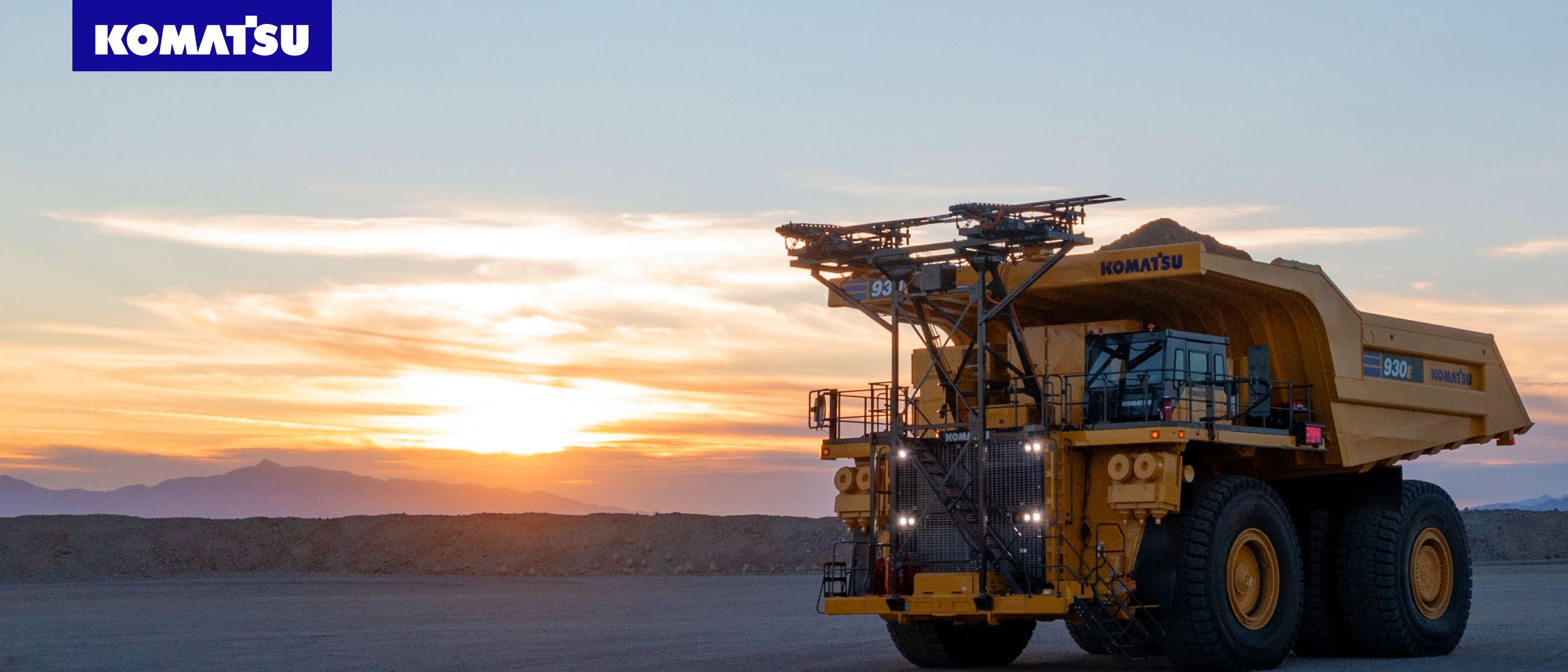

Automating megawatt charging:

Komatsu's foundation for safer and scalable mining ultra-class electric fleets

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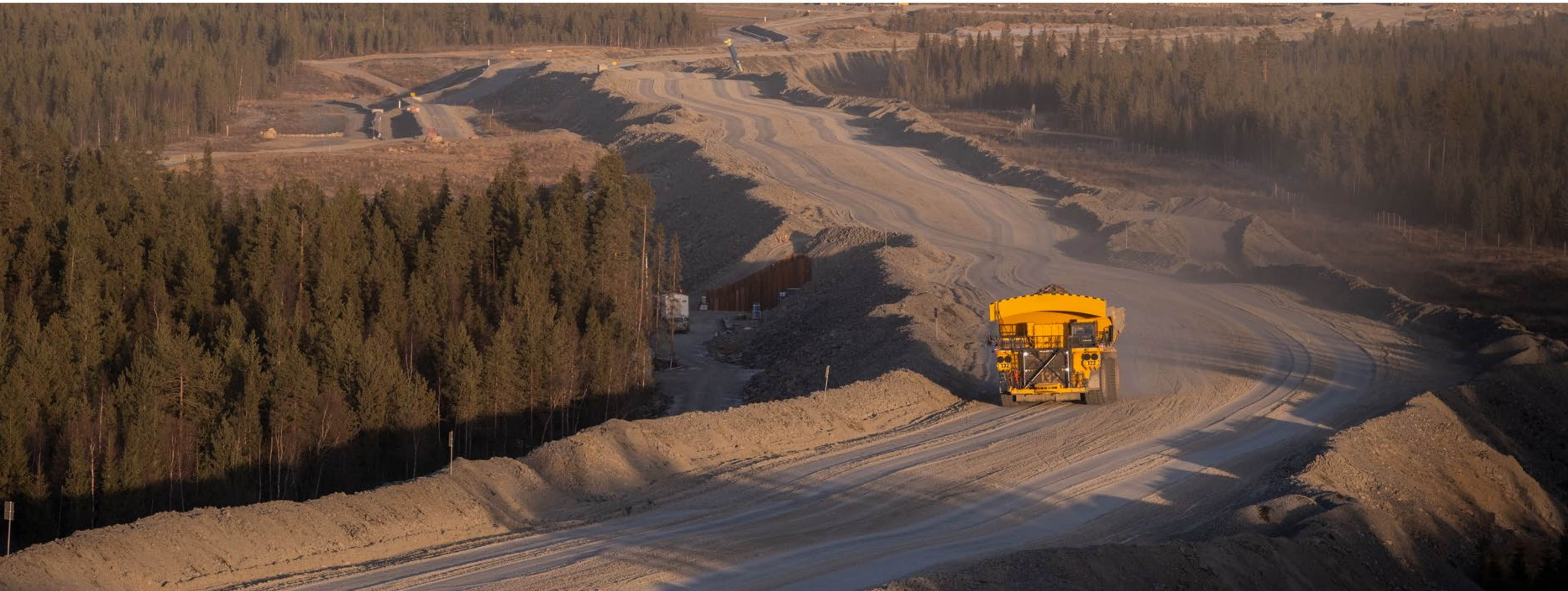
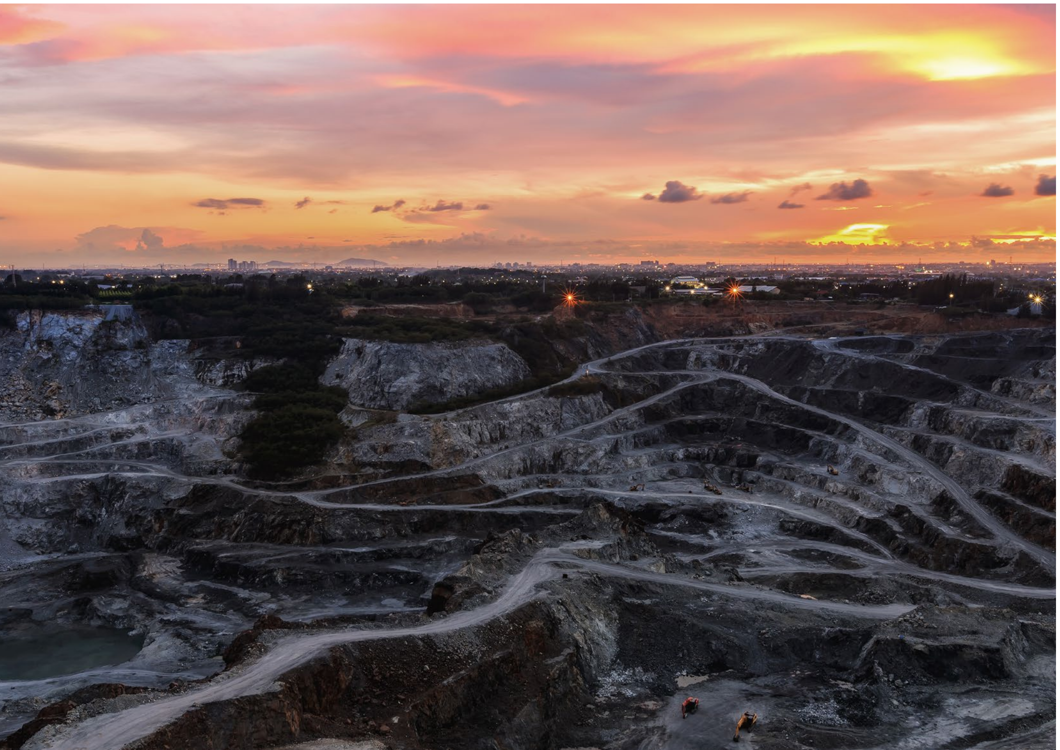
Abstract

As ultra-class haul trucks transition to battery-electric platforms, mining operations will transition to megawatt-scale charging within tightly constrained production cycles. At this scale of power and energy, charging becomes a safety critical and time critical industrial process. Manual charging may introduce variability in connection quality, charging duration and availability, while also increasing exposure to high energy electrical interfaces to operators while in harsh operating environments. Without a more controlled and standardized approach, charging can quickly limit fleet productivity, disrupt autonomous workflows and complicate grid and energy management as fleets increase in scale. The recommendation to industry is that solutions such as automated megawatt-scale charging systems designed as production infrastructure rather than auxiliary equipment. Automated connection devices, standardized communication and control and integration with fleet and energy management systems enable charging to be repeatable, verifiable and optimized.



Charging of ultra-class electric haul trucks

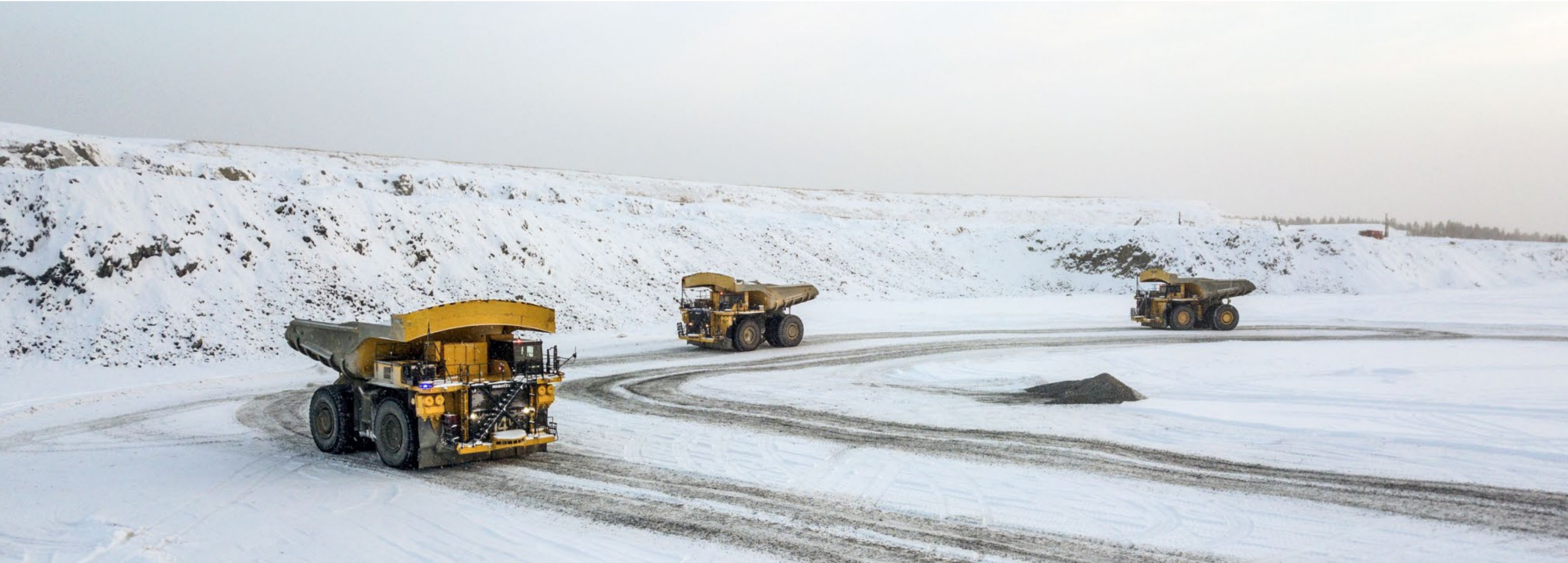
For future adoption of battery electric ultra class haul trucks, the mining industry will require megawatt scale energy transfer capabilities to sustain production levels while meeting decarbonization commitments. At these power levels, conducting charges manually will become a constraint on operations. Having an operator manually conduct charging operations at several megawatts of electrical power introduces avoidable safety exposure to high voltage equipment, increases cycle time variability and limits fleet scalability. In contrast, using automated systems to conduct charging operations provides an opportunity to mitigate these avoidable conditions. Additionally, integrating automated charging systems with autonomous haul fleets, fleet management applications and energy management systems helps establish a foundation for future interoperability through emerging standards for megawatt charging and automated connection devices (ACDs).

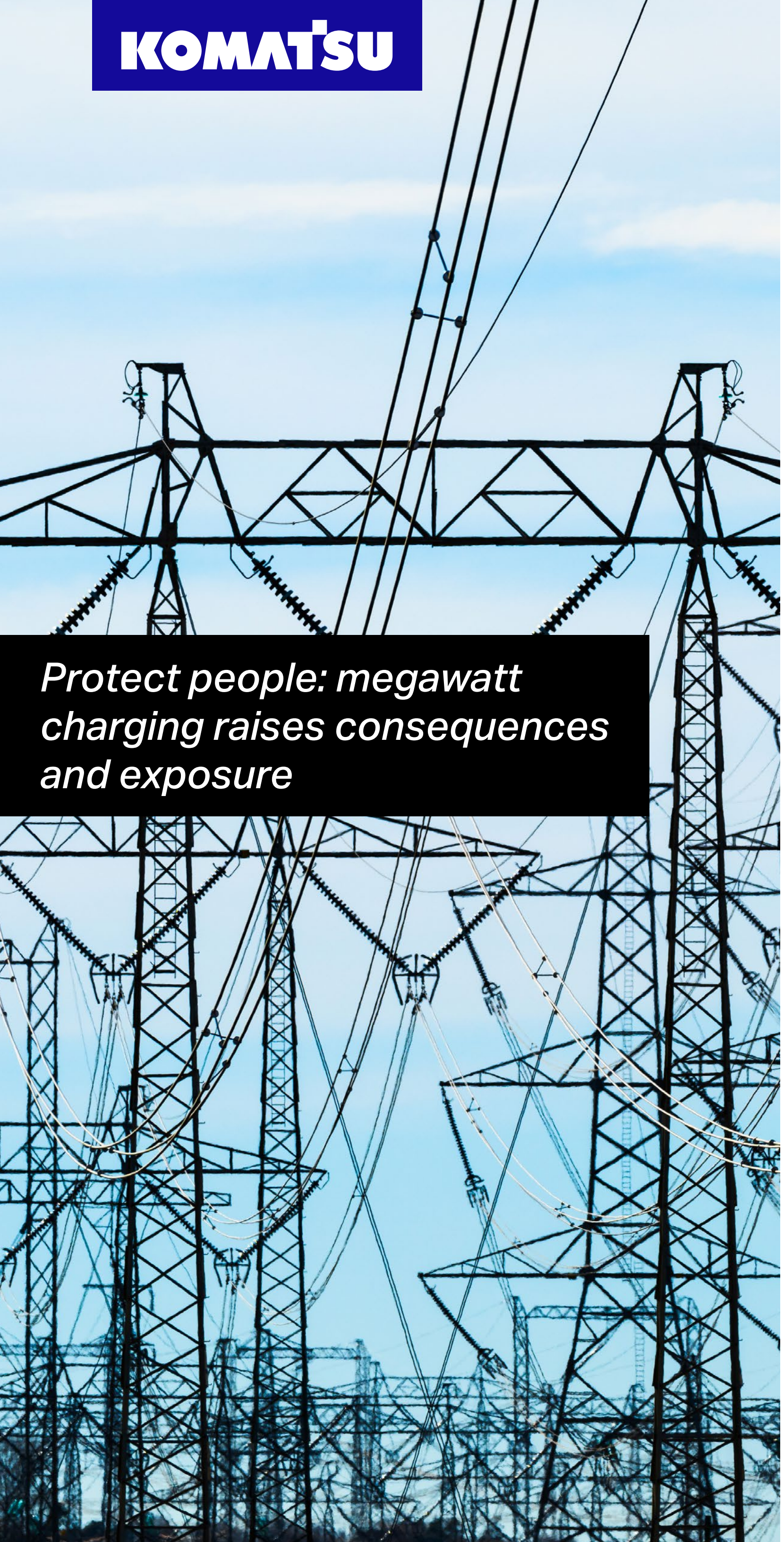


Ultra class battery electric vehicle (BEV) haulage is a charging problem disguised as a vehicle problem

Ultra class haulage duty cycles are defined by tight queues for loading haul trucks, steep grade segments and continuous 24/7 operations. The source of energy for haul trucks will shift from being produced on board via internal combustion engines (ICE) and fuel, to drawing the energy from the utility power grid. To draw this energy effectively and efficiently for surface mining applications the charging interface and process must become as industrialized as the truck itself. Mining original equipment manufacturers (OEMs), such as Komatsu, and electrical infrastructure suppliers, such as ABB, are already developing and demonstrating automated fast charge systems designed for harsh mine environments reflecting the sector's recognition that charging must be engineered as a production system. Two trends make automation essential rather than optional, power escalation and operational autonomy.

- **Power escalation:** Transitioning from hundreds of kW toward multi MW charging drives performance targets to extremely high currents/voltages for heavy duty off-highway applications, pushing new requirements and solutions in thermal management, connector design and handling, and safety standards.
- **Operational autonomy**: Mines are moving toward increasingly automated and autonomous operations. Charging of battery electric haulage and other equipment and vehicles must not remain a manual "last step" that breaks autonomy.





Protect people: megawatt charging raises consequences and exposure

Charging must be automated to protect people, protect production, and protect the grid

Charging battery-electric vehicles (BEVs) at the Megawatt scale manually introduces hazards that escalate nonlinearly with power: arc flash energy, thermal run-away risks from poor contacts and high voltage safety concerns. Power specifications in such applications emphasize isolation/safety, touch protection, thermal limits and situational awareness; all of these areas require human performed actions or procedures which present safety risks due to variability and environmental conditions (dust, mud, vibration, ice), required PPE (electrical safety gear) and the training and awareness of the person who is performing the work. Mine sites are 24/7 operations and such conditions can put people at risk.

ACDs are explicitly created to address this. SAE J3105, an industry standard developed by SAE International, defines performance, communication, control, mechanical and safety requirements for conductive automated connection devices so charging can occur without an operator leaving their seat and in a repeatable manner. This keeps an operator in a safe position to monitor the system and allows the opportunity for more powerful and efficient charging events.

Why manual charging doesn't scale safely:

- **Repeated human proximity:** high-voltage interfaces during coupling/decoupling elevates exposure to electrical hazards and can increase exposure to risks.
- **Inconsistent connector engagement:** increases contact resistance leading to fault likelihood, especially with contaminants and wear in harsh environments.
- **Process compliance:** manual operations lead to inherently higher safety risks at 24/7 mine sites and necessitate a comprehensive compliance program including PPE, site policies, flash boundaries.

Automation mitigates these issues by shifting safety enforcement from "training and habit" to engineered interlocks, sensors and verified states.

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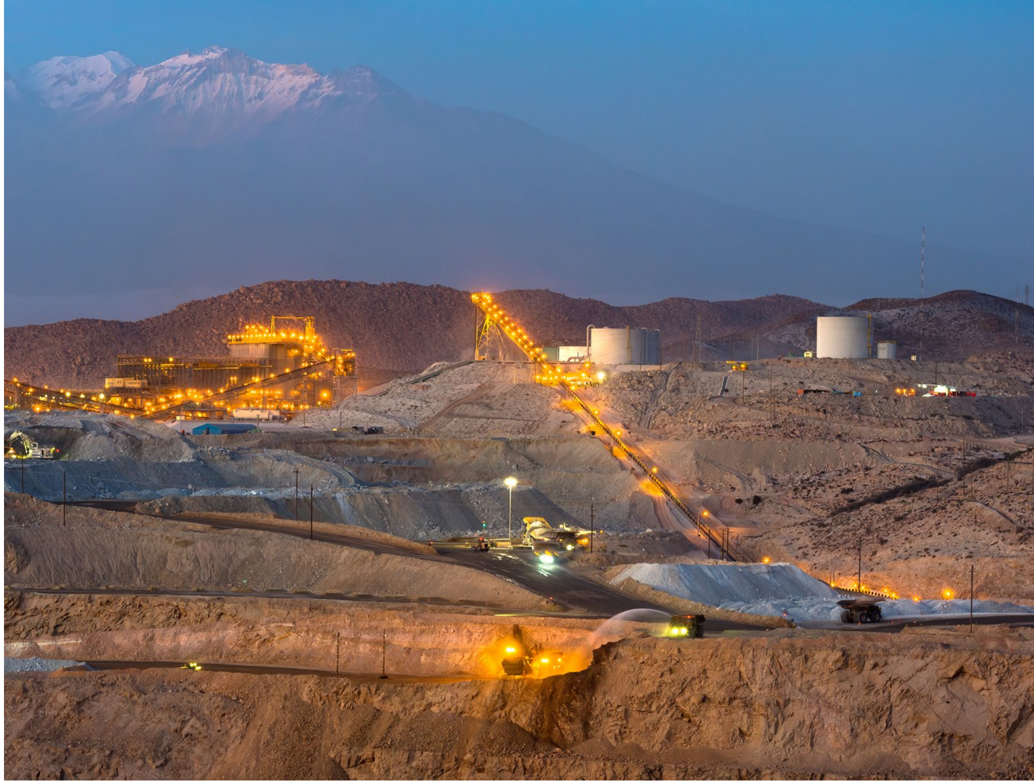
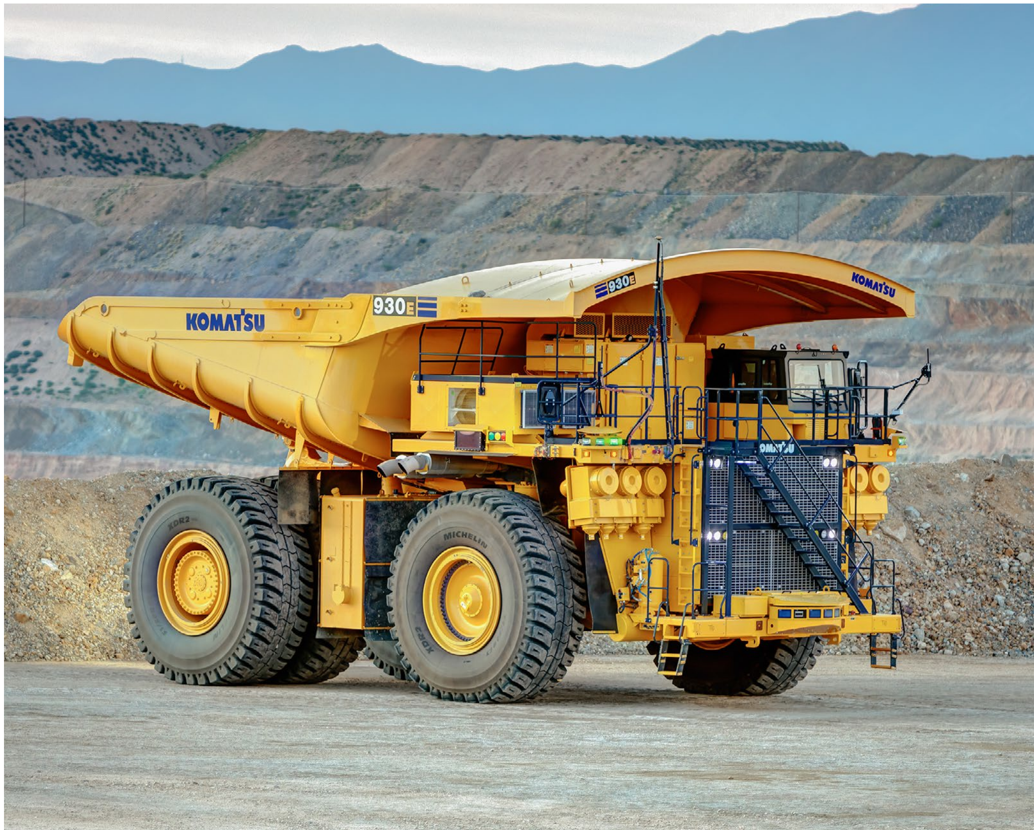
Variability is the enemy of fleet electrification

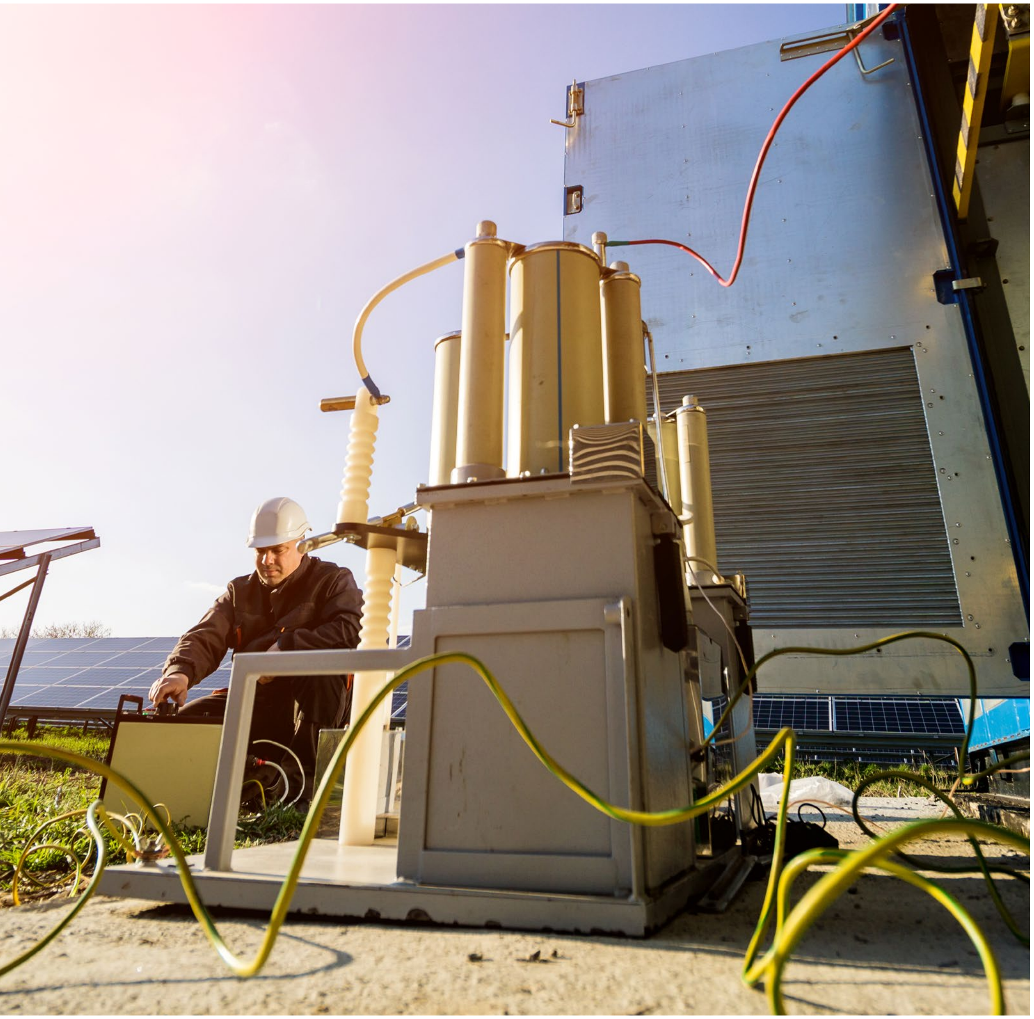
Many mines that use ultra class haul trucks are optimized to the point where supervisory systems dictate the real time routes and timing of haul trucks throughout the mine to minimize queuing and general downtime of these machines; small delays can propagate into lost tonnage and therefore lost revenue. Manual charging introduces unpredictable alignment times, connector handling times and availability and risk to human resources. Automated systems reduce variance by making charge events a deterministic subroutine which is consistent, repeatable and efficient.

Protect production: automation's productivity benefits

Automation enables reduced cycle times, automated connecting, and is faster and more consistent than manually handling charging cables while wearing heavy PPE. This consistency may be realized in operational cost savings that are factored in the total cost of ownership of the aggregate charging system and vehicle. Opportunity charging may be leveraged for efficient charging during natural pauses, such as spotting, breaks or shift changes. This concept becomes feasible only when connection is quick and reliable; such an operation would be nearly impossible to achieve manually. Finally, higher charger utilization may be achieved via automation allowing for integration with other automated tools on the site, such as autonomous haulage systems (AHS) or fleet management systems (FMS). Leveraging the combined ability of these tools may create opportunities for scheduled or real-time charge windows, reducing down time and increasing productivity. Reducing the time that the truck will need to be stationary is easily recognized as operational cost savings, but the speed and consistency of automated charging opens up additional efficiency gains which may create further savings and increases in production.







Scalability: manual processes do not scale like hardware

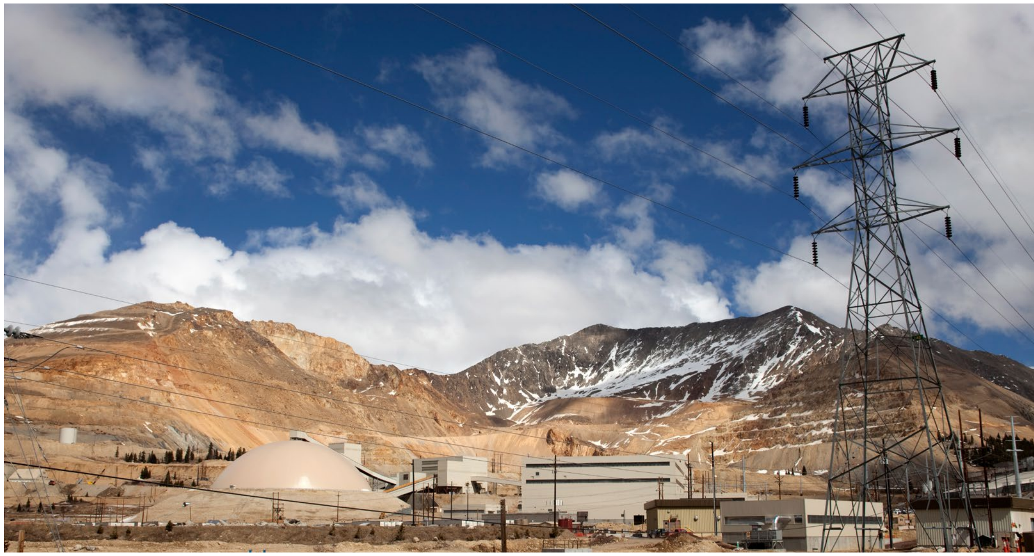
A fleet of five to ten trucks might cope with manual handling of charging cables; a fleet of 50–150 cannot. The scaling limits are:

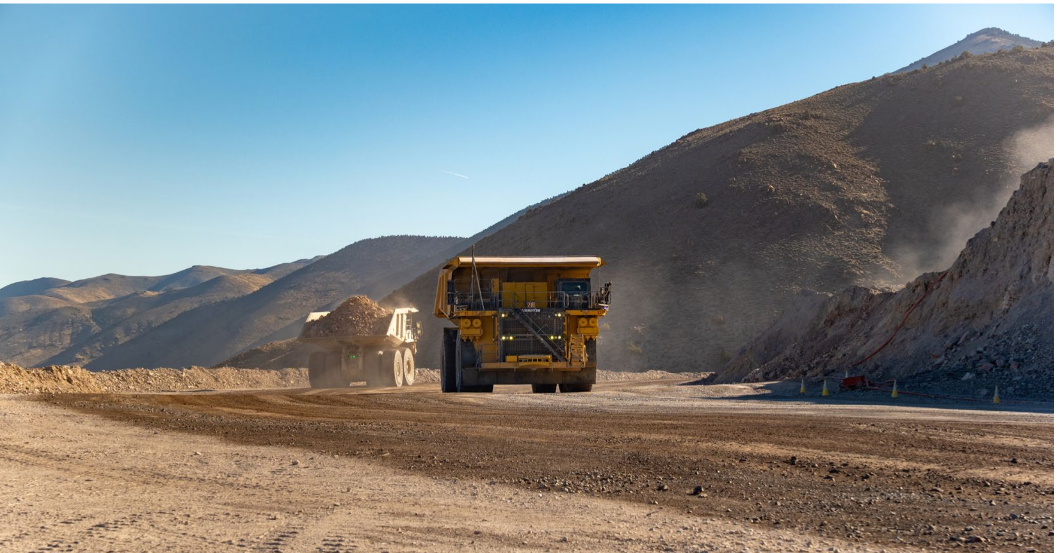
- **Trained labor availability:** Regular manual operation of high-power chargers would require resources stationed at the charger whenever a haul truck required a charge session. When considering a site wide fleet of electric haul trucks, a person would need to be stationed at a charger through all operating shifts and at multiple chargers.
- **Error and safety incident rates:** Automation technology has proven that such systems are very good at conducting repetitive tasks fast and with high levels of precision. Operators are prone to fatigue and vulnerability to environment which may drive increases to safety incidents and bodily injury.
- **Procedural drift:** Manual operation of high-power chargers will require strict operating procedures and PPE due to the levels of voltage and current involved. The requirement of such measures inevitably will result in deviations emerging in the field due to fatigue, creating safety risks for equipment and personnel.

Automated connection and control turn charging into infrastructure that scales similarly to other mine systems (conveyors, crushers, substations) with standardized maintenance and monitoring.

Grid and energy management: charging must become dispatchable load

Fast charging at MW scale can dominate a mine's energy demand. The technology necessary to charge ultra-class haul trucks is poised to drive standards which will emphasize robust communication and control. The scale of energy and equipment size highlights the need for integration with digital systems to monitor and optimize energy usage for site assets in real time. Automated charging integrated with fleet management and energy management systems enables peak shaving / demand management via coordinated charging schedules and existing site systems. The flexibility of power allocation across chargers based on fleet priorities, and across existing major electrical loads on site, such as tethered shovels, trolley systems, crushers, etc. Finally, data fed into energy management and fleet management software enables closed loop control using vehicle SOC, routes and site power limits. Achieving these functions is difficult with manual charging operations conducted by individuals in the field; the system relies on procedural controls and communication which diminishes optimization and efficiencies that may be realized with the use of automation.





Functional requirements for automated ultra class haul truck charging

Automated connection (physical layer)

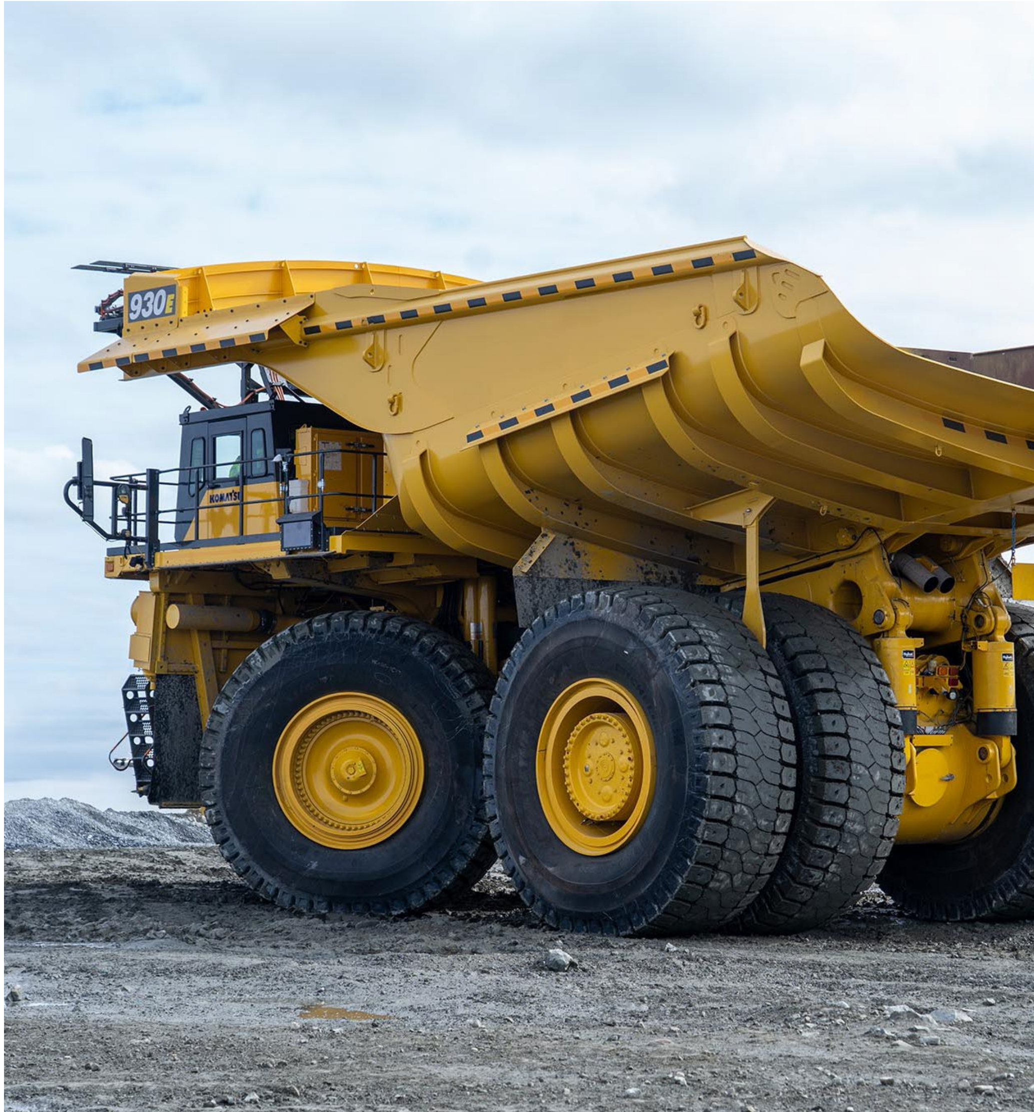
At megawatt power, cable mass, stiffness, cooling requirements and connector forces drive the need for automated handling. Two established approaches, pantograph / overhead ACDs (common in bus opportunity charging and adaptable to off road) covered by SAE J3105 sub documents, or robotic guided connectors capable of compensating for vehicle position variation and harsh conditions. The connection system must be capable of automated alignment sensing, contamination tolerance or cleanliness strategies and thermal management capability for high current operations.

Automated safety and interlocks (electrical + functional)

Automation must enforce "verified safe state" before energization. To achieve this, a charging system must incorporate established standards within the on-highway battery electric vehicle and charging market. Such standards call for insulation monitoring and isolation checks, contact temperature and thermal derating monitoring, arc detection / fault detection and rapid shutoff. One addition to these existing standards will be personnel presence detection in hazard zones, required for the power levels of the charge and the automated machinery.

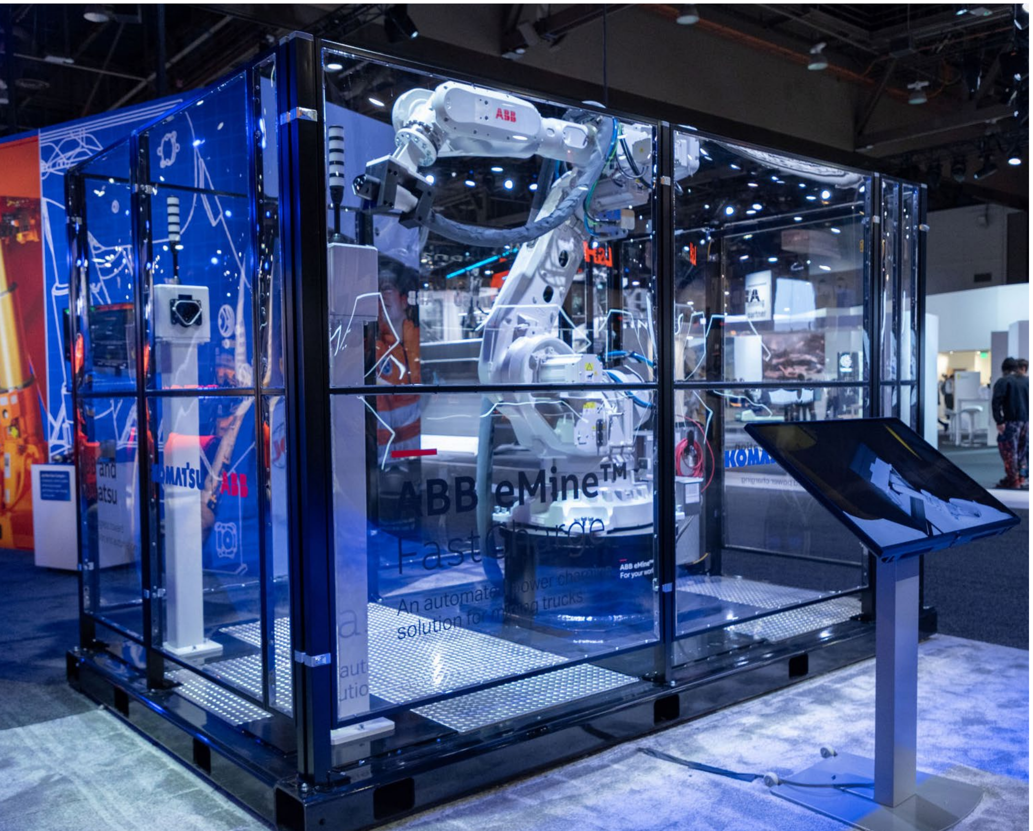
Communication and control (digital layer)

High power charging requires standardized, reliable communication between the vehicle and the vehicle charger. The on-highway market uses established communication protocols for familiar charger interfaces on both personal and industrial electric vehicles, such as the combined charge system (CCS). The CCS chargers leverage an ISO 15118-2 and the megawatt charging system (MCS) uses a derived version of this standard, ISO15118-20. Leveraging the existing standards reduces barriers to technology adoption and enables interoperability. Additionally, the use of standards and design that matches the on-highway industry allows for a more robust supply chain, commercial off the shelf convenience and greater flexibility for obsolescence.



Economic argument: automation lowers total cost of ownership (TCO)

While automation adds initial capital investment (robot/ACD, sensors, controls), it reduces operating costs and protects revenue through efficiencies in battery electric haul truck operation and maintaining production goals. The value drivers in charger automation are higher availability, reducing charger connecting times, consistency in charging sessions and minimizing haul truck down time. There may be fewer safety incidents resulting from operators being distanced from the high-power charging systems, reducing costly stoppages or more importantly, injuries. Finally, reduced infrastructure may be realized by leveraging additional automation tools with charging, such as energy management and fleet management systems.



Reference architecture (conceptual)

An automation ready charging ecosystem for ultra class BEV haul trucks typically includes:

Battery electric truck
- Battery + BMS
- Charge inlet/ACD interface
- Telematics and charge control (ISO 15118 aligned)

High power charger
- MW scale power conversion
- Liquid cooled conductors/contacts (as required)
- Metering and power quality monitoring

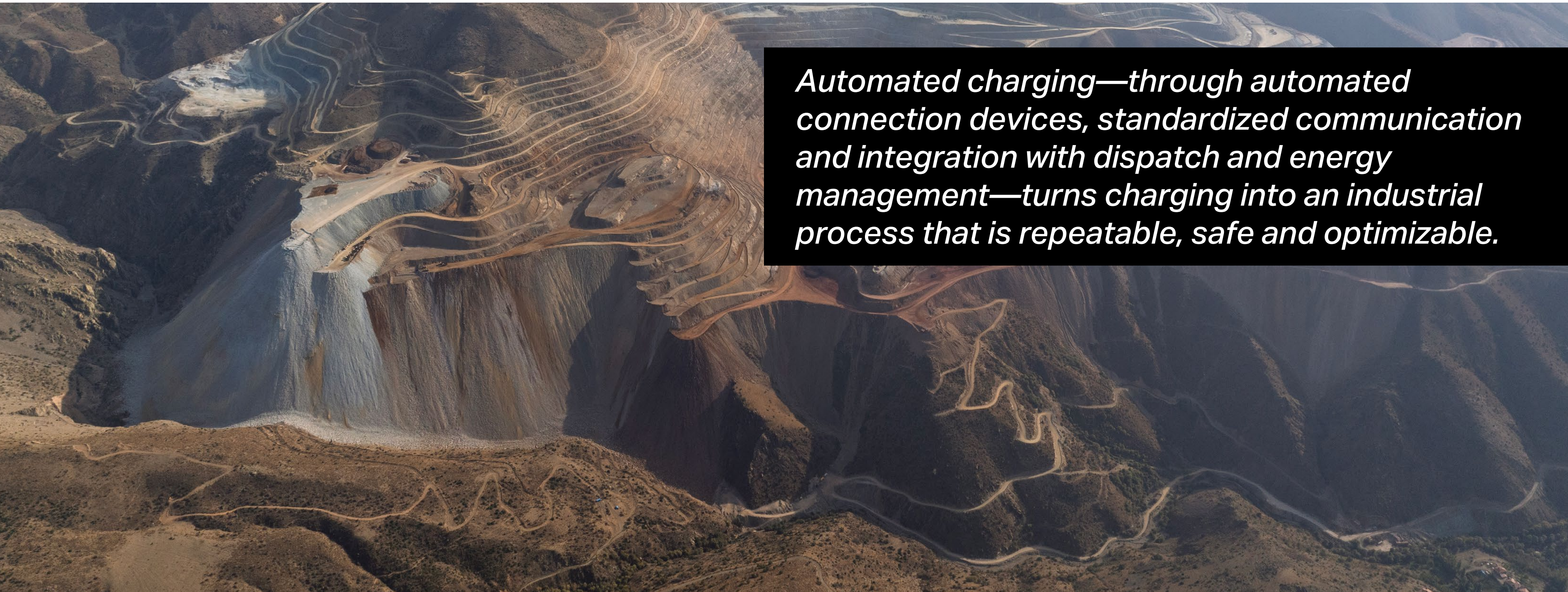
Automated connection device
- Automated connection device capable of adequate articulation, reach, and precision to plug a charge connector into a battery electric haul truck
- System tolerance to account for truck alignment and environmental condition variables

Site energy and fleet management
- Fleet management system
- Charging integration into a fleet management system (priority rules, SOC targets, queue management)
- Microgrid/EMS interface for demand management

Conclusion

For ultra class battery electric haul trucks, charging is a critical production system, requiring operation at extreme power levels. The operational, safety and scalability realities of mining make manual charging a bottleneck and a risk vector. Automated charging—through automated connection devices, standardized communication and integration with dispatch and energy management—turns charging into an industrial process that is repeatable, safer and optimizable. The industry direction toward MCS and established work on conductive automated connection devices (SAE J3105) underscore that automation is not speculative; it is the enabling layer required for large scale BEV haulage.

Komatsu is actively leading this transition. Through targeted investments in electrification, automation and energy management, and through a dedicated center of excellence focused on decarbonization, the company is developing the systems and infrastructure required to make ultra-class battery electric fleets viable at scale. This work is driven by a global network of engineers and strategic partnerships working to solve the industry's most complex challenges, from megawatt charging to integrated fleet and energy optimization. By aligning equipment innovation, digital integration and talent, Komatsu is not only adapting to the future of mining, it is also helping define it by delivering solutions that enable safer operations, protecting productivity and accelerating the path to decarbonized mining. of mining, but helping define it by delivering solutions that enable safer operations, protect productivity and accelerate the path to decarbonized mining.



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Key risks and mitigations

Risk	Why it matters	Mitigation
Connector/ ACD reliability in harsh environment	Downtime cancels electrification gains	Ruggedized designs, sensor redundancy, condition monitoring, contamination management
Non standard interfaces / vendor lock in	Stranded assets as fleets diversify	Adopt standards aligned approaches and interoperability requirements in procurement
Grid constraints and demand charges	MW peaks can be costly	Automated scheduling, power sharing, EMS integration

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