



A yellow autonomous haul truck is shown from a top-down perspective, driving on a wide, light-colored dirt road in a mining environment. The truck is positioned in the center of the frame, moving away from the viewer. The surrounding terrain is rugged and dusty, with some sparse vegetation visible in the upper corners.

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A COMPARISON OF TECHNOLOGIES FOR  
DECARBONIZING MINING

# Electrifying haulage

The mining sector is responsible for up to seven percent of global greenhouse gas emissions [1]. In view of this, ABB is applying its eMine™ framework of methods and solutions to resolving the many questions surrounding the decarbonization of mining transport and associated electrical infrastructures, including vehicles, material loading and unloading points, charging stations, battery chargers, and batteries.



Diesel-powered transportation systems within mines are a major contributor to the industry's carbon emissions.

Electrification reduces ventilation requirements and improves working conditions.



This article discusses different approaches to electrification.

One of the primary contributors to carbon emissions within mining operations is the haulage of materials, a process heavily reliant on diesel-fueled transportation systems. Not only do these systems account for a substantial part of the mining industry's CO<sub>2</sub> emissions [2] but they also increase ventilation requirements for underground mines, which can amount to as much as 70 percent of total operational costs [3]. Therefore, alternative solutions such as trolley assist systems, battery-operated electric trucks, electric conveyors, and electric hoisting systems offer significant promise in facilitating the overall transition to carbon neutrality.

Considering the vast scope of this transformation, simulation has emerged as an indispensable tool in understanding the benefits and addressing the challenges arising from the introduction of such alternative technologies. Against this background, ABB has applied its simulation tools to investigate questions around the decarbonization of material haulage with trucks, and its impact on the associated electrical infrastructure. In view of this, ABB uses simulation tools built on a discrete event simulation (DES) framework. These tools focus on modeling relevant changes in the internal states and outputs of haulage equipment and associated electrical infrastructures such as stationary (eg eMine™ FastCharge) and dynamic energy transfer systems (eg, eMine Trolley Systems) →01. They recalculate and log parameters whenever

triggered by events such as interactions between the multiple systems considered in a simulated scenario. In a mining environment, a brief list of the assets involved includes vehicles, material loading and unloading points, charging stations, battery chargers, and batteries.

The application offers a comprehensive set of features designed to tackle the complexities of real-life mine sites. Its graphical user interface eases the modeling and comparison of various truck and conveyor-based hauling methods. Trucks are modeled based on their underlying propulsion technology, ranging from traditional

**A built-in scenario planning feature makes it possible to explore different hauling scenario variations within the same mine.**

diesel to diesel-electric and battery-electric vehicles and are matched with the required electrical infrastructure for stationary charging or dynamic power transfer systems. The functionality to import Drawing Interchange Format (DXF) files, a format designed for sharing data universally across computer aided design (CAD) applications, allows for the direct translation of

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#### Electrical premanufactured room with:



MV-switch-gear



Rectifier



3-winding  
rectifier  
transformer



Protection  
and  
auxiliary  
systems



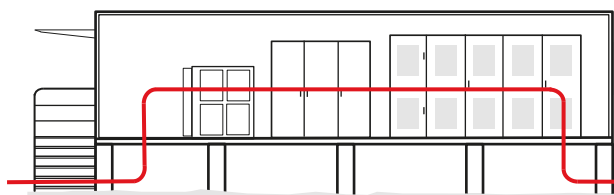
Control and  
monitoring  
systems



Digital  
services



HVAC and  
pressur-  
ization



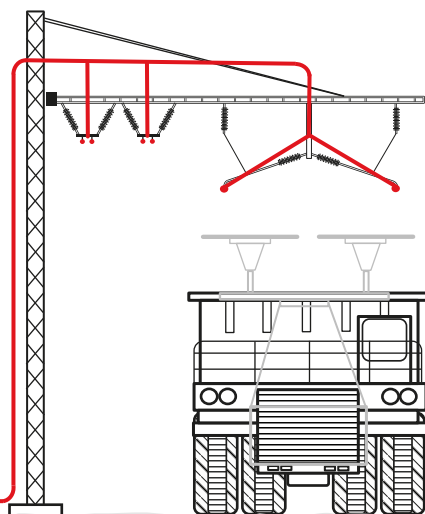
#### Overhead line system, poles and foundations:



Poles and  
foundations



Overhead line  
and catenary  
system



### E-MINE™ TROLLEY SYSTEM

The ABB eMine Trolley System comprises a substation and catenary OHL (overhead line). The sub-station connects to the mine power distribution network (medium

voltage), converts AC to DC power, and delivers it via the OHL to the truck(s).

Compared to diesel-powered trucks, a trolley system can avoid up to

90 percent of CO<sub>2</sub> emissions for the electrified trucks running on the system and achieve higher productivity, enabling up to 2x the truck's speed on the trolley line.

Find out how ABB's trolley system is supporting the transition to all-electric mines.



— 01 ABB's eMine™ Trolley System dramatically reduces diesel consumption and emissions.

— 02 Characteristics of the path considered for simulation results.

— 03 Energy consumption in kWh per cycle as a function of haulage path length and elevation gain.

entire existing mine layouts into the nodes and edges forming the directional graphs that model its road network. A built-in scenario planning feature makes it possible to explore different hauling scenario variations within the same mine. Scenarios can be split into multiple time frames, allowing users to consider different road networks, graphs, electric infrastructures, hauling trucks and productivity parameters during the distinct stages of the life of a mine.

### Energy consumption per haulage cycle

Load-and-haul operations in mines are characterized by the cyclic paths of vehicles. Such haul cycles will typically change over the lifetime of a mine. Here, the study estimates energy consumption over a haul cycle based on the distance and altitude difference from source to destination. Energy values are calculated for a 290 t payload truck.

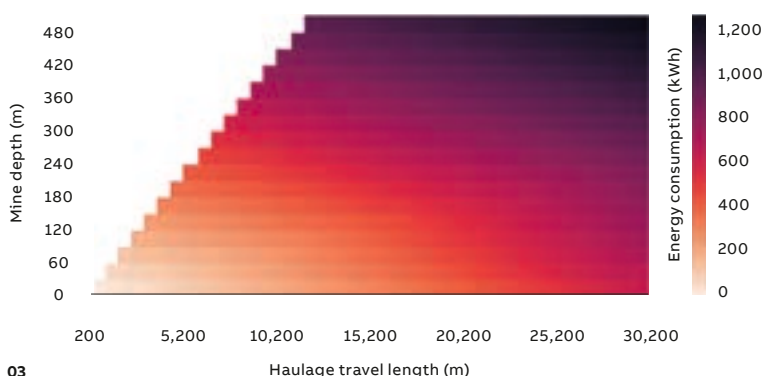
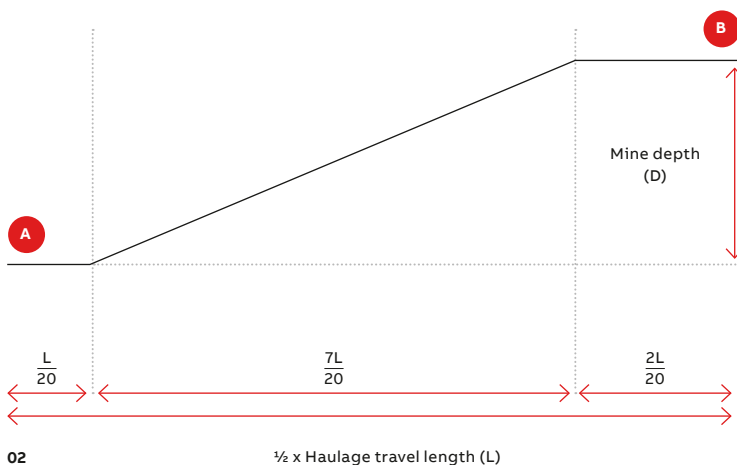
The energy consumed during a haul cycle is important. For electrified trucks without a combustion engine, this is the energy that must be supplied by an electrical infrastructure to ensure their operation. Compared to a diesel tank, which stores sufficient energy for a full shift, batteries can supply only a few haul cycles at most.

Disruptive changes in battery cell technology, leading to a significant increase in energy and/or power density, are considered by the authors to be unlikely in the foreseeable future. In consequence, the results presented here will remain valid for the first generation of haul trucks equipped with batteries. The types of paths considered for the simulation are shown in →02. Trucks start at location B, travel to location A, where they are loaded, then return to B to be unloaded. The total travel distance and the elevation gain in the described cycle are denoted L and D respectively.

The values in →03 correspond to the energy needed for a truck to travel along a track, for different lengths and depths (L, D) of track. The study notes that for a fixed length L, the maximal considered D is set such that the slope in the middle segment of the haulage profile does not exceed 12 percent, signifying that segments over which the slope would exceed this maximum are omitted within the analysis of the illustration. Typically, haulage road slopes in open pit mines do not exceed 10 percent.

### Three haul cycle scenarios

Every mine is unique – thus, for an exact analysis of the energy consumption within a given mine, one should conduct simulations tailored to the mine's own geography and characteristics. Nevertheless, the objective of this discussion is to



For an exact analysis of the energy consumption, simulations tailored to the mine's specific geography are needed.

offer overarching insights that can be universally applied to various sites based on representative simulations. The three distinct combinations of lengths and depths chosen to approximate the haulage within generic types of mines are summarized in →04.

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04 Representative scenarios simulated with the simulation tools application\*.

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05 Diesel fuel required to travel unloaded to material source and loaded back to material destination, in the three scenarios.

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06 Reduction in diesel consumption and CO<sub>2</sub> emissions resulting from integration with electric power.

—  
07 Reduction in cycle time resulting from use of trolley-powered propulsion.

## Four propulsion systems

### 1. Diesel

Although diesel is still the main propulsion technology in the mining industry, the transition to electric propulsion systems is well underway. In this context, the diesel fuel required to travel L/2 unloaded to the material source and L/2 loaded back to material destination in the three scenarios is simulated in →05 as a reference point for comparing the CO<sub>2</sub> emissions to be reduced in today's mining operations, where a conversion factor of 2.66 kg CO<sub>2</sub>/liter is considered.

|            | Type of mine, example | Depth D (m) | Haulage path length L (m) | Energy needed to complete haul cycle (kWh)* |
|------------|-----------------------|-------------|---------------------------|---------------------------------------------|
| Scenario 1 | Iron ore mine         | 150         | 5,000                     | ~ 336                                       |
| Scenario 2 | Cobalt mine           | 200         | 10,000                    | ~ 492                                       |
| Scenario 3 | Copper mine           | 500         | 15,000                    | ~ 1,043                                     |

04 \*Scope 1 and 2 carbon intensities of the electrical energy consumed depend strongly on the local energy mix and have thus been set to zero for the purposes of this study.

|            | Depth D (m) | Haulage path length L (m) | Diesel consumption per cycle (l) | CO <sub>2</sub> emissions (kg) |
|------------|-------------|---------------------------|----------------------------------|--------------------------------|
| Scenario 1 | 150         | 5,000                     | 105                              | 279                            |
| Scenario 2 | 200         | 10,000                    | 154                              | 407                            |
| Scenario 3 | 500         | 15,000                    | 318                              | 840                            |

05

|            | Depth D (m) | Haulage path length L (m) | Diesel consumption per cycle (l) | CO <sub>2</sub> emissions (kg), Diesel only |
|------------|-------------|---------------------------|----------------------------------|---------------------------------------------|
| Scenario 1 | 150         | 5,000                     | 16                               | 41                                          |
| Scenario 2 | 200         | 10,000                    | 26                               | 67                                          |
| Scenario 3 | 500         | 15,000                    | 34                               | 91                                          |

06

|            | Depth D (m) | Haulage path length L (m) | Diesel cycle time (min) | Diesel-assist trolley cycle time (min) |
|------------|-------------|---------------------------|-------------------------|----------------------------------------|
| Scenario 1 | 150         | 5,000                     | 15.2                    | 9.6                                    |
| Scenario 2 | 200         | 10,000                    | 22.5                    | 13.9                                   |
| Scenario 3 | 500         | 15,000                    | 42.3                    | 23.9                                   |

07

### 2. Diesel-assist trolley

One of the dynamic energy transfer methods used today for haulage trucks is equipping a diesel-electric haul truck with a pantograph. This requires a trolley line and feeding substation system, preferably on selected inclined segments of the haul route. When connected, the drive-train draws energy directly from the electrical infrastructure to propel the vehicle, enabling the combustion engine to shift into idling mode, reducing diesel consumption.

An overview of the diesel consumption and CO<sub>2</sub> emissions for the representative cycles simulated with ABB eMine™ Simulation Tools is provided in →06. For the simulation, the assumption is that a trolley line has been installed over the entire upward ramp of the trajectory (0.35 L).

Furthermore, trolley-powered propulsion enables a significant reduction in cycle time as summarized in →07.

In →08 the relationship between diesel consumption (in liters) and the proportion of trolley-equipped ramp is shown. The graph considers the three distinct simulated scenarios, each corresponding to different mine depths and track lengths, highlighting potential reductions in fuel as the proportion of the trolley-supplied power increases.

### 3. Battery trolley with in-motion charging

The following section focuses on battery-trolley propulsion technology, an innovative approach involving in-motion charging. Here, the energy supplied by a trolley line is used for propelling a vehicle and simultaneously charging its battery,

Battery-trolley propulsion technology is an innovative technique used for propelling a vehicle while charging its battery.

thus taking the place of a diesel engine. It is noteworthy, however, that this technology is not yet fully established but is experiencing rapid evolution thanks to active research, development, and pilot projects [4].

To analyze the potential benefits of this technology on battery utilization, →09 shows battery energy based on maximum charging power, as well as on the proportion of trolley-equipped ramp, with each curve accounting for a different

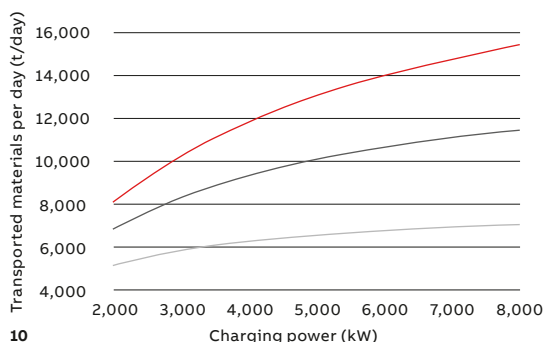
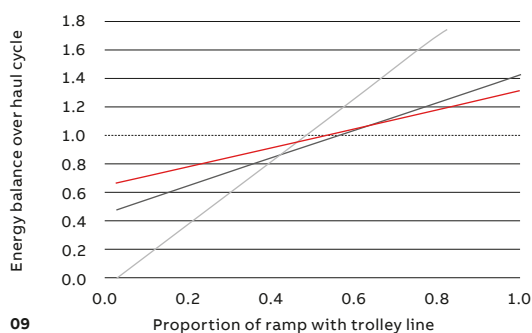
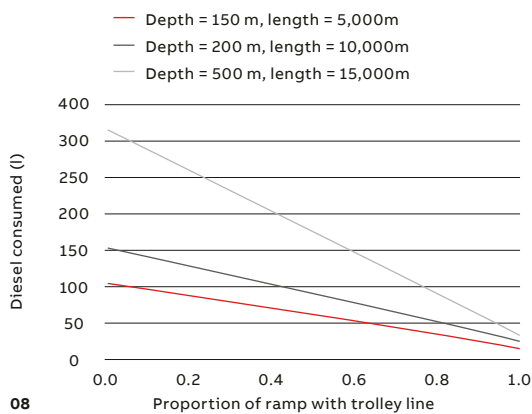
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08 Diesel consumption in liters per haul cycle as a function of the proportion of the ramp equipped with a trolley line.

—  
09 Energy balance over a simulated haul cycle assuming maximum charging power of the battery while on trolley.

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10 Productivity in metric tonnes of materials hauled per day as a function of installed charging power.

simulated depth and length. The purpose is to enable an assessment of operational requirements for an intended haul cycle within three identified regimes:

- Sections without trolley infrastructure where a hauling truck would rely solely on stationary charging technologies to overcome the energy required to complete the cycle.
- Sections with partial trolley coverage but with a residual energy deficit. In such instances, the hauling truck would require a combination of in-motion charging from the trolley line and supplemental stationary charging to meet the overall energy demands of the haul cycle.
- Sections with sufficient trolley coverage to allow for dynamic recharge of the entire energy needed to complete the haul cycle.



In the simulations, it is further assumed that the truck is equipped with a 1.5 MWh battery and that the recuperation of braking energy is enabled during downhill operation.

#### 4. Battery with stationary charging

Stationary charging plays a pivotal role in the decarbonization of mining trucks. It involves strategically placing temporarily fixed stations along haul routes to efficiently recharge or swap truck batteries. Ideally, stops are scheduled and placed such as to minimize downtime. While widely adopted for passenger cars and buses, the application of this technology in mining haulage – particularly open-pit – poses distinct challenges regarding feasibility and economic

Charging stops are scheduled and placed such as to minimize downtime.

viability. In this context, the primary challenge arises from the significant energy demand for transporting materials out of a pit. Under these circumstances, batteries must store all the energy needed to bridge the distance and elevation between two charging stations. Assuming one charging station along the haul cycle, this implies ensuring sufficient coverage for a truck to safely travel from and to material handling and charging points.

To assess the influence of stationary charging, →10 shows productivity measured in tonnage of material transported per day. Assuming 21 operating hours and 290 t of materials hauled per cycle, the simulated productivity is plotted against the charging power of a simulated stationary charger for a mining truck equipped with a 1.5 MWh battery. Again, the braking energy is recuperated to recharge the battery during downhill operation.

#### Study of payload classes

While the previous section assumed a 290 t payload truck model, this section will analyze the impact of payload on energy consumption per haul cycle. It must be noted that for the different payloads studied here, mostly only diesel and diesel-trolley propulsion technologies are commercially available.

| Payload | Simulated mine type | Depth D (m) | Haulage path length L (m) | Energy per haul cycle (without recuperation) (kWh) | Possible recuperation energy (kWh) |
|---------|---------------------|-------------|---------------------------|----------------------------------------------------|------------------------------------|
| 100 t   | Iron ore            | 150         | 5,000                     | 118                                                | 24                                 |
|         | Cobalt              | 200         | 10,000                    | 172                                                | 27                                 |
|         | Copper              | 500         | 15,000                    | 352                                                | 84                                 |
| 240 t   | Iron ore            | 150         | 5,000                     | 261                                                | 53                                 |
|         | Cobalt              | 200         | 10,000                    | 381                                                | 60                                 |
|         | Copper              | 500         | 15,000                    | 791                                                | 185                                |
| 360 t   | Iron ore            | 150         | 5,000                     | 387                                                | 74                                 |
|         | Cobalt              | 200         | 10,000                    | 566                                                | 82                                 |
|         | Copper              | 500         | 15,000                    | 1,163                                              | 256                                |

11

11 Since vehicle input parameters, such as the rimpull propulsion curves, frontal areas, or specific energy efficiencies, depend on the engineering of truck models, the results shown are approximate for the respective payload class.

Diesel-trolley technology makes it possible to linearly reduce diesel consumption and CO<sub>2</sub> emissions dependent on the installed trolley line length. Going one step further, replacing the diesel engine with a battery pack offers the possibility of also recuperating braking energy during downhill operation. These potential recuperation gains are illustrated in →11.

If this technology is paired with a trolley infrastructure to supply energy while moving, continuous operations can be achieved in cases where the energy supplied to the battery when connected to the trolley line is sufficient to run on the off-trolley segments. In the current study, it has been determined that, to sustain the operation, a minimum of around 60 percent of the uphill haulage path must be equipped with a trolley system. If determined to be feasible given the mine's operational constraints, in many cases it will be economical to install longer trolley systems because the energy cycled through each truck's battery is further reduced, extending its lifetime, and thus reducing cost.

When using stationary charging for electric haul trucks, flexibility is increased, but productivity is reduced because trucks must stop for recharging. However, with higher-powered charging infrastructure, this problem can be mitigated.

Thanks to its simulation tools application, ABB can assess the feasibility of a solution over the life of a given mine.

Nevertheless, one challenge lies in the fact that key parameters of new technologies, such as costs and performance, still have uncertainties. This applies particularly to truck technologies that have not yet been commercialized.

All in all, many technology-related questions remain, such as: the choice of battery technology, battery capacity, and truck payload size; the choice of where to place trolley lines and stationary charging infrastructure and related installed capacity; and predictions of the number of trucks needed. However, by taking operational and infrastructure constraints into account with the simulation tools application, ABB can address these questions during the early phases of a project from a technological and economic point of view and assess the feasibility of a solution over the life of a given mine. •

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