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Future of mining: Lessons from Sweden's first BEV mining loaders- and trucks deployments

D. Olsén[a], D. Rutqvist[b] and P. Sundqvist[c]
[a]*Boliden Mineral AB, Garpenberg, Sweden*
[b]*Sandvik Mining and Rock Solutions, California, USA*
[c]*LKAB, Gällivare, Sweden*

ABSTRACT

This article looks at the groundbreaking introduction of battery electric vehicles (BEVs) to the mining industry, with an in-depth look at their first use in Sweden. As the world continues its transition to more sustainable and environmentally friendly practices, the mining sector has begun to embrace BEV mining loaders and trucks as a potential game-changer. This article highlights key takeaways from Sweden's pioneering efforts to integrate BEV technology into mining operations in terms of sustainability, productivity, and overall operational excellence.

The performance results and practical experience not only contribute to the growing body of knowledge on sustainable mining practices, but also provide valuable lessons for mining operations worldwide considering the adoption of BEV technology. Sweden's experience serves as an important reference point for the mining industry's journey towards a greener and more efficient future.

Experiences from the first BEV deployments in the Swedish mining industry are shared by Boliden Mineral AB, LKAB and Sandvik Mining and Rock Solutions.

1 INTRODUCTION

There is a broad global consensus on the importance of reducing fossil fuel emissions and limiting global warming to 1.5°C above pre-industrial levels. Under the Paris Agreement of 2015, more than 190 countries have committed to reducing greenhouse gas emissions. Companies today face increasing pressure from customers, the financial sector, societal stakeholders, and regulators to act and demonstrate progress in reducing their climate impact. The mining industry is no exception.

In October 2021, the International Council on Mining and Metals (ICMM) announced its commitment to achieve net zero greenhouse gas emissions by 2050 or earlier. This document (ICMM., 2021) has been signed by all members (including Boliden), which together represent one third of the global mining industry. Many major mining companies that are not members of ICMM have adopted similar or more ambitious targets, including LKAB, see Table 1 below.

Table 1 Boliden's and LKAB's climate targets

Company	2030 (base line 2021)	2045	2050
Boliden	42% lower CO_2 (scope 1&2)		Net zero
LKAB	25% less CO_2 in total 30% lower (2026) for MUJ: Malmberget Underground	Net zero	

As in most industries, the majority of a mine's emissions are directly or indirectly caused by energy use. The mining industry uses large amounts of energy in its operations. Both electricity for mainly stationary equipment (such as crushers, elevators, pumps, ventilation, process equipment) and liquid fuel for vehicles and other machinery. Energy is not only a major CO_2 emitter for mineral and metal extraction companies, but also a significant cost item. It often represents 10-15%, and in some cases even more, of the value added in production (Svemin. 2023).

The transition to fossil-free and renewable electricity use is well advanced and long lasting. Reducing the use of liquid fossil fuels has often proved more difficult and the transition has started later, but this is now changing rapidly thanks to technological developments. Various electric equipment will play an important role in this transition, such as battery-powered trucks and loaders. Their diesel versions are by far the largest consumers of diesel fuel in a typical mine.

The use of BEVs in the mining industry has accelerated sharply in the last 2-3 years due to a combination of factors;

- Industry drive to reduce emissions
- The introduction of new machine models from suppliers such as Sandvik
- Rapid developments in battery technology for higher capacity and lower cost
- A BEV business case that makes sense for more and more companies
- Government incentives and regulations to reduce emissions

As many as one in three underground mines today can expect a lower operating cost per ton with BEVs compared to conventional machines, considering not only the initial cost but also productivity and indirect benefits such as reduced ventilation requirements.

While the mining industry, like all other industries, will transition to fossil-free energy use in the long term, the speed of the transition will largely be determined by short-term business benefits. The business benefits of BEV for an underground mine can be grouped into three themes:

A. Local working environment
B. Mining economy
C. Global sustainability

The following section provides a brief overview of these issues based on Sandvik's global experience. This will then be illustrated locally in the Nordics/Sweden with experiences from LKAB and Boliden.

2 BEV AND LOCAL HEALTH AND SAFETY

No new technology or method that can reduce greenhouse gas emissions would be acceptable for implementation if it had a negative impact on local health and safety. An important element in the introduction of BEVs in mines is therefore to consider the impact on factors such as local air quality and the generation of heat, noise, and vibration from machinery. Modern BEV technology has shown a very high potential for improvement in these areas.

The implementation of BEVs in mines is most advanced in North America, where a large number of machines have been in operation for up to a decade. Trials on Sandvik machines (Acuna., et al. 2022) have shown:

- Reduced energy consumption per ton-kilometer by 70-80%, most of it waste heat, thanks to a more energy-efficient drive train. Lower heat emissions improve the working environment and reduce the risk of fires during maintenance. It can provide opportunities for savings in ventilation (see next section).
- Reduced levels of dust and silica in the air, as BEVs do not create an air stream with exhaust emissions that "stir up" particles from the ground. In some cases, over 70% reduction in respirable dust has been measured.
- 100% reduction in diesel particulate emissions.
- Reduced external noise from 120db to 100db, which is a 100 times reduction in sound intensity as the decibel scale is logarithmic.
- Less vibration from the machine with a positive impact on perceived fatigue. Measured through operator surveys.

Overall, the move to BEV has great potential to improve the working environment for operators, technicians and others working with and around the machines.

3 BEV AND MINING ECONOMICS

An economic comparison between conventional and battery electric fleets can quickly become complex and must consider factors such as purchase price, operating costs, and productivity. There are also indirect cost impacts such as ventilation requirements and carbon taxes. There is not space here to provide an exhaustive overview, but the most important considerations are highlighted.

Sandvik has conducted dozens of life cycle cost analyses for BEVs with customers around the world, and in many cases BEVs have already proven to be economically competitive. However, local factors such as electricity cost, diesel price, mining method, ore body geometry and possible policy instruments play an important role.

In general, BEVs are significantly more powerful than conventional machines because the electric motors and batteries can provide better acceleration, higher speeds, and more torque. As a result, BEVs have the potential to increase productivity, often by as much as 20%, for mines and applications where speed and power are limiting factors. Typical examples are heavy trucks moving material up a ramp, where the diesel engine is the limiting factor in how fast the machine can go.

Batteries for a BEV fleet represent a significant investment for a mine, and the economics of batteries are largely determined by the amount of fuel saved. In some markets, diesel fuel is heavily subsidized, and it can be difficult to pay for the batteries through fuel savings. Roughly speaking, a diesel price of SEK 12-14 per liter is required for the fuel savings to financially offset the investment in batteries. The price of electricity is often less important, as BEVs use around 80% less energy than an internal combustion engine for a given transport operation, and electricity costs are therefore only a small part of the total operating costs.

Even in operations with low fuel costs or little opportunity to increase productivity, BEVs can be economically viable due to other operating costs. An electric powertrain is in many ways simpler than an internal combustion engine, with fewer moving parts, less maintenance, and fewer spare parts.

However, these benefits can take time to realize, as new technologies often require more maintenance during the introduction phase as the organization is trained and learns how to optimize operations. Once BEV fleets have stabilized, it is not uncommon for maintenance costs to be as much as 20-30% lower than a conventional fleet.

In terms of indirect cost impact, ventilation tends to be the most significant. Ventilation is a key factor in an underground mine and accounts for a large proportion of both capital investment and operating costs. Many mines move more air than metal to maintain a safe and comfortable working environment.

A BEV fleet reduces the need for ventilation due to lower emissions of both heat and airborne particles. A conventional fleet of machines can account for 30-50% of the total heat generated in an underground mine. Switching to an electric fleet can reduce heat generation by up to 80-90%. Together with the reduction in particulate emissions, ventilation requirements can be significantly reduced. This can result in lower capital and operating costs. Lower capital costs, as less extensive ventilation infrastructure can be installed, and lower operating costs, as ventilation tends to be a large consumer of electrical energy. It often accounts for 40-50% of a mine's electricity consumption.

Electric machines therefore not only reduce the size of the ventilation infrastructure required, but also the amount of airflow. You can move less air through the mine and still have the same effect on air quality. This means that even cold mines that need to heat air can save energy because less airflow means less air to heat. The greatest economic gain in ventilation is achieved in new mines or expansion projects where the entire ventilation system can be based on an electric fleet. There are mining projects where the ventilation savings alone will pay for the entire transition to BEVs.

The interaction between BEV and ventilation can, in some cases, lead to the somewhat counter-intuitive result that net electricity consumption is reduced in the transition to BEV. Even after considering the energy required for charging. Example simulation (figure 1) from (Rutqvist., et al. 2023). Figure 1 shown below.

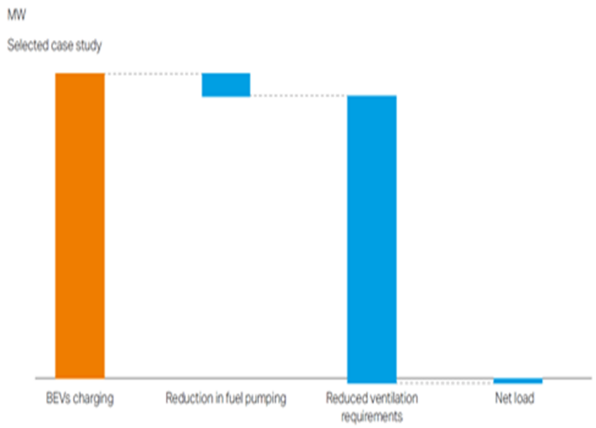

Figure 1 Example of change in electrical load after BEV introduction.

To summarize this section, below is an example of a total cost analysis in a typical case with trucks working on a ramp. In the scenario depicted (figure 2, Rutqvist., et al. 2023) a CO_2 value of 50USD/ton is assumed and the mine in question cools the air and can adjust the design and operation of the ventilation system. In this case, the total cost of the BEV is comparable to a conventional fleet, as maintenance and fuel savings outweigh the higher capital cost of machinery, batteries, and charging. In addition, there are savings in ventilation and CO_2, resulting in a lower total cost when indirect benefits are considered, see Figure 2 below.

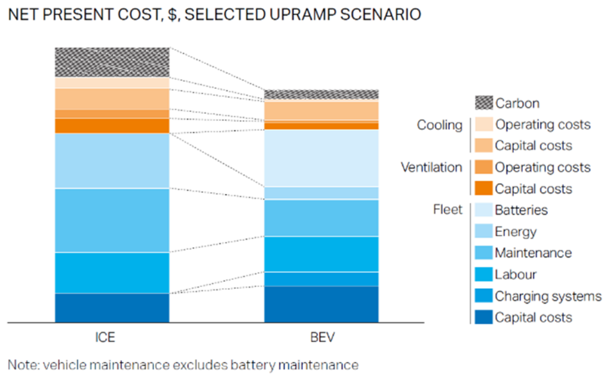

Figure 2 Total cost analysis for ICE (internalcombustion engine) vs. BEV (battery electric vehicle) fleet.

4 BEVS AND GLOBAL SUSTAINABILITY

Typically, over half of the total CO_2 emissions from an underground mine come from the heavy vehicles. Of these, trucks and loaders consume by far the most fuel, as they also perform the heaviest transport work. This can be as much as 30-50 liters of diesel per hour for machines working around the clock. LKAB alone uses around 40 million liters of diesel per year (Lundstrom., 2022. Swedish).

The climate benefits of converting heavy-duty vehicles to BEVs depend largely on the energy used to charge the machines. The emission intensity in CO_2 per kilowatt-hour differs greatly between the different types of energy, see Table 2 below.

Table 2 Emissions intensity

Type of energy	Kg CO2 / kwh
Coal	0.90
Gas	0.50
Diesel	0.26
Nuclear and renewable energy	0.01

Since a BEV uses only 20-30% of the energy of an internal combustion engine to perform the same work, the emission intensity of the electricity charged can be significantly higher than diesel and still provide reduced emissions.

Depending on the type of machine and application, coal-fired electricity can still reduce CO_2 emissions by 0-30%, gas-fired electricity by around 50% and nuclear or renewable electricity by up to 100%. In mines where the BEV is used to reduce the energy consumption of the ventilation system, this emission reduction should also be considered and thus a double CO_2 gain.

5 EXPERIENCE OF IMPLEMENTATION IN SWEDEN

5.1 Boliden

5.1.1 Background

As mentioned above, Boliden has set clear targets to become a carbon neutral company. By 2030, the goal is to reduce CO_2 emissions (Scope 1&2) by 42% compared to the base year 2021, which will be achieved, for example, by gradually replacing diesel vehicles with alternative energy sources. Several different projects are being carried out within Boliden to achieve these targets, including a collaboration between Boliden Garpenberg and Sandvik to test and evaluate a new battery electric loader.

5.1.2 Boliden Garpenberg

Boliden's mine at Garpenberg is an underground mine. It is one of the deepest mines in Sweden, reaching a production depth of almost 1,500 meters. The primary minerals are zinc, lead, and silver, while the secondary minerals are copper and gold. Total annual ore production is approximately 3.3 million tons and is expected to increase in the future. The design of the Boliden Garpenberg mine in terms of depth and extent makes it particularly complex for the implementation of new technologies such as battery machines, mainly due to infrastructure such as power supply and operational planning of these vehicles.

5.1.3 Battery loader project

At the end of August 2023, a Sandvik Toro™ LH518iB was delivered to Boliden Garpenberg (figure 3). It was the first machine of its kind to be introduced to the market, including both battery power and automation. The aim of the project is to be involved at an early stage and to learn and understand what it means to put a battery loader into operation. This in the context of the conditions that currently exist in the operations, see Figure 3 below.

Figure 3 Sandvik Toro™ LH518iB at Boliden Garpenberg, Sweden.

5.1.4 Battery operating conditions

At an early stage of the project, a site for the charging station was selected, located on level 1232 in Lappberget, one of the ore bodies at Boliden Garpenberg, and adjacent to potential production in the area. The charging area has dimensions of approximately 10x15 meters, which allows two machines to be parked on the width, but more importantly, allows the two batteries to be loaded and unloaded in parallel. A slewing crane has also been installed to facilitate cable management for the operators when changing the batteries. A 1,000V supply to the charging bay powers two chargers and a cooler in the charging station, see Figure 4 and figure 5 below.

Figure 4 Level 1232 charging bay with two chargers and a cooler.

Figure 5 Charging bay with swing arm installed.

The project includes a service agreement with Sandvik, which includes the maintenance of the batteries. This means the project has three batteries. Two in operation at any one time and one for service and balancing, which is then rotated within the operation. To ensure that the batteries are maintained, a service station with a charger and a cooler has been installed in the workshop on level 1225.

5.1.5 Progress

To date, the battery machine has been operated both manually and by line-of-sight (radio control) within the break room. It is operated by two operators within the project who take shifts every two weeks. This means that the machine is used for a maximum of one shift per day, seven days a week, as opposed to the normal operation of two shifts per day. The reason for having dedicated operators for the battery machine was initially that a few would learn how to operate the machine, and particularly the new step of changing the batteries. More operators are now gradually being trained on the battery charger, see Table 3 below.

Table 3 Accumulated operating data for the battery machine

Operating hours	Production	Distance covered	Energy use	Reduced CO2
507 h	71 kton	1,870 km	35.4 MWh	approx.42 tons *

*Compared to the average consumption of an equivalent diesel machine (Sandvik Toro™LH517i).

5.1.6 Automation and future testing

The loader fleet at Boliden Garpenberg currently consists of six Sandvik Toro™ LH621s and two Toro™ LH517s, with approximately 80% of the operating hours on automation. Therefore, an important step in evaluating the battery machine is to run it with automation. In mid-March, the automation software is expected to be implemented in the machine and the control room system to start these tests. Part of these tests will be to understand how productivity compares with the diesel machines.

Another test will be the delivery of batteries to the production areas. To reduce the time spent in the ramp to and from the charging station (which equates to lost production time), the possibility of driving the battery to the machine is being investigated. This in combination with Sandvik's "Flexible Safety Zone", where the possibility of more light gates in the production area makes it possible to unload the battery inside the outer light gates while production continues inside the innermost light gate.

5.1.7 Lessons learned and observations

The general impression of the machine is that it performs very well. The main advantages experienced by the operators compared to diesel machines is that full torque is immediately available on both the drive train and the bucket.

Because of the power in the drive, this has in turn meant that the driving pattern, especially when unloading, has changed, and adapted compared to the diesel machine. When driving manually, the machine is much quieter and there is much less dust and particles in the air. When driving up ramps, there is plenty of power and the machine does not slow down. Figure 6 shows a worker at Garpenberg next to the LH518iB machine underground.

Compared to the larger Sandvik Toro™ LH621i and the (manual) tests carried out so far, the battery machine has a lower overall capacity and does not quite achieve the same tonnage per hour. In one of the tests carried out, ore was transported from an ore bin directly to the crusher, a distance of approximately 450m. During the test, the battery machine achieved 187 tph with an average of 15.8 t per bucket and the diesel machine achieved 199 tph with an average of 20.5 t per bucket. The big advantage for the battery machine is the difference in speed on the incline, where the difference is almost 10 km/h, which means that the battery machine completed about 25% more laps than the diesel machine, see Figure 6 below.

Figure 6 Worker next to LH518iB in the underground charge bay.

However, it is too early to comment on the long-term productivity in terms of maintenance and automation, as well as mileage in mining areas.

Some advantages of the battery machines that Boliden generally sees are:

- Higher power, efficiency, and maneuverability.
- Presumably higher utilization and productivity (due to fewer maintenance hours).
- Long-term environmental, safety and health benefits for the mining environment.

5.2 LKAB

5.2.1 Background

Global greenhouse gas emissions must be reduced significantly and within a short period of time. Tackling the climate problem will require a transformation – a significant challenge as global energy consumption is heavily linked to fossil fuels. It requires systemic changes that will take time and require a high degree of collaboration between industry and policy makers.

In light of that, LKAB has destined itself a goal towards a transformation for a sustainable future for the industry. They have set the target to completely remove CO2 emissions from the processes and products by 2045.

The core three pillars of this transformation include:

a) New World standard for Mining
b) Carbon Free Sponge Iron
c) Critical Minerals

5.2.2 LKAB - Malmberget (MUJ)

It came to Malmberget's fortune to pioneer the workflow and lead this transformation. To attain an overhaul of their value chain, devoid of any CO2 emissions they needed to begin in a rather controlled manner. So, there are no lose bolts when adapting this development as a routine in their operation close to 2045 and beyond.

The target set for Malmberget is to cut down 30% of CO2 emissions from its mining and process value chain by 2026. This ambitious target required LKAB to go back to the drawing board and assess where they need to focus their approach. LKAB saw the areas that could be tackled first was the Load and Haul operation. Since, the highest consumption across the mining value chain for diesel is by their loaders and followed up by trucks.

A simple approach was followed, as shown in Figure 7.

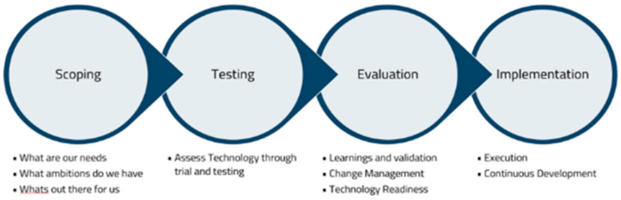

Figure 7 The approach.

LKAB is fortunate to have strong partners to collaborate with in achieving this target like Sandvik. As LKAB came to a decision to test and evaluate battery driven truck and loader. For a high production mine their target was to go for higher payload and at the time of agreement the truck was the biggest available battery powered underground dumper and the loader remains as one with highest payload capacity for underground operations.

In discussions around emission free machinery, LKAB do at times limit highlighting how much improvement battery powered equipment can bring in improving the work environment for operators both working on the machine and in near vicinity. With no diesel fumes, no noise, lower dust emissions due to no exhausts. LKAB is transforming the operators safety and wellbeing through this introduction as well.

5.2.3 Evaluation

One of the early learnings for introducing Battery electric machinery was introducing awareness. So, education and training of operators and mine workers was key to help them understand the way of working and hear their ideas around the changes.

With an LFP (Lithium Iron Phosphate) battery chemistry, they were understood to be comparatively safer with respect to them going into thermal runaway. LKAB has seen the challenges of lower charge density that comes with these batteries, so the battery size is presumed to be bigger for higher availability for operation.

The second key aspect for BEV had been the need for infrastructure. In a high production brownfield operation that has diesel fueling points in multiple locations; allocating a specific drift for a single vehicle seemed far fetch but with the opportunity to have equipment that can change a battery weighing 9 tons by itself and charging power of 350 kw, LKAB understood it may not be long for this design to be limited for one machine only. With high power charging and innovative swapping technology; the charging stations can be used same way as diesel fueling points. What is important is where the location can be, so it does not become a bottle neck for routine traffic.

Current trucks hold a payload capacity of 90 ton, and they are road legal vehicles capable of being driven (thanks to LKAB's road infrastructure) up to 40 km/h (loaded) and 50 km/h (unloaded) and the haulage route is completely flat. This proved to be a challenge for the Sandvik TH550B; first from the speed as it could not be driven beyond 19 km/h. This limited its productivity in isolated condition but at the same time created a risk for production and traffic for regular site fleet. But what was interesting was the energy consumption of the machine. A challenge foreseen for the future includes how much energy is needed and the cost of energy will be a key driver for operational efficiency. This was well received. For Sandvik TH550B was capable of performing the same cycle with 40% less energy needed (if LKAB convert diesel liters to Kwh).

But this machine is part of LKAB's future strategy, and we anticipate changes in our operational layouts and practices. Therefore, multiple cycles were evaluated by driving the Sandvik TH550B down the ramp with loads and driving up empty. Here LKAB observed the key advantage of battery equipment from operational perspective, Regenerative energy. The overall net energy consumption for each kilometer for 40% less than one would experience in a flat route operation.

This proved to be better outlook for future production requirements if they want to optimize their operational availability, increase utilization, and minimize energy consumption, see Figure 8 below.

Figure 8 "Control room of the future" built to handle all Autonomous applications, located at the 1250m level in Malmberget Mine.

5.2.4 Sandvik Toro™ LH518iB

Sandvik Toro™ LH518iB will prove vital in this journey for Malmberget, as it not only will be supporting in the journey towards emission free mining but as well will introduce autonomation into Malmberget operation with LHDs. Even though the payload capacity is less than the typical Sandvik Toro™ LH621i but with high acceleration and high power, they expect that it will exceed or at least match the bigger size loaders. LKAB's learnings around charging routines gained from Sandvik TH550iB may further be cemented as LKAB approach new areas, new shifts and new people to test and evaluate machinery that will be changing the future of the industry, see Figure 9 and figure 10 below.

Figure 9 LH518 in the charging bay.

Figure 10 LH518iB front view.

5.2.5 Learnings

Some key learnings for LKAB throughout the evaluation process have been how the change management for the transition to such fleet with new needs would look like. LKAB start again in the same pattern with infrastructure; how many and where do they need charging stations. Today it is one truck; if LKAB expand this operation to five trucks, in what routine shall these set up look like. This question has brought LKAB the discussion on how many batteries do they need as these batteries are key assets themselves for maintenance. Do LKAB envision on an improved monitoring system, where operator share the batteries between multiple trucks and the swap based on the information on where the higher power battery is.

Another challenging but fortunate learning is that Sandvik TH550B does not have standardized charging set up; for future it may be quite challenging for mine operators to have diverse fleet set up requiring different charging equipment or cables.

The tramming battery has been observed to be promising on flat surfaces and can be a potential aide in moving batteries for servicing like a forklift or relocating the machine in case of emergency.

With new technology, one such challenge always comes is how current routines need to be adapted. Currently has been water ballasting tires for the machines and introducing that routine for a battery powered truck does need some rethinking. The tonnage capacity for the truck had to be reduced to support this routine and LKAB do anticipate that the energy consumed with excessive rolling resistance caused by the water ballasting was rather higher. But it is a work in progress, if we do not try, we never learn.

6 CONCLUSION

The future of mining must be socially, economically, and environmentally sustainable, which requires a gradual phase-out of fossil fuels. The introduction of BEVs will play a central role, along with fossil-free power generation and other solutions. Electrification of mobile machinery benefits the environment by reducing diesel use and the long-term sustainability and profitability of the mining industry. With BEV technology, mines can increase their competitiveness through increased performance and lower maintenance costs, while improving the working environment and minimizing negative impacts on the global environment.

Swedish mines are important sources of metals and minerals that are crucial to produce renewable energy, electronics, batteries, and other technologies central to the transition to sustainability, including electric cars. The growth of rechargeable vehicles in Sweden will increase by 30% in 2023, and the number of pure electric cars will reach almost 300,000 in December 2023 (Marc. 2024). According to the forecast, the number of electric cars in Sweden will reach 1.7 million by 2030, an increase of 1,600% compared to the beginning of 2022.

It would be ironic if the mining industry provided all the iron, copper and other resources needed to expand renewable energy production, charging infrastructure, electric cars and batteries - but did so with fleets of fossil fuel-powered machinery. The sustainable transition is enabled by the mine, and the transition must start at the mine. As this article shows, companies do not have to compromise on safety, the environment, or economics to be part of the solution.

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