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Unleashing potential | Lasting impact

Power at the end of the tunnel. Electrifying underground mining.

May 2023

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Disclaimer

This white paper was developed and is intended for general informational purposes only. The findings, interpretations and conclusions presented in this white paper are the result of a collaborative process between Sandvik and Partners in Performance.

The results from the techno-economic modelling presented in this white paper are based on assumptions using the latest information available at the time and chosen to be representative of a typical (or “average”) underground mining operation. Each mining operation or project should assess the technical and economic viability of Battery Electric Vehicles on a case-by-case basis through individual, detailed and independent studies.

Factors affecting the underlying assumptions may change over time (e.g. energy prices, costs, performance of battery electric fleets) and the companies are under no obligation to provide updates or correct this document as a result. Modeling choices are the propriety of Sandvik and Partners in Performance.

This white paper also contains references to third party research, data and industry publications: no warranty is given to the accuracy and completeness of external information.

Foreword

Sandvik

The Sandvik Code of Conduct ("It's in our hands") includes a clear commitment to environmental responsibility – operating our business and providing products and services in a way that minimizes environmental impact and contributes to a more sustainable future. We are dedicated to using engineering and innovation to make the shift that will drive more sustainable business, setting targets in line with the Science Based Targets initiative (SBTi), consistent with the Paris Climate Agreement of keeping global warming below 1.5° C, with the goal of becoming a net-zero carbon emissions company by 2050 at the latest.

We are not alone in this important drive: the International Council of Metals and Mining (ICMM) has announced a similar commitment, its members representing a third of the global mining industry – and Sandvik is proud to be leading the race to help mining companies achieve their own sustainability goals, specifically in terms of electrification.

It's not just about reducing emissions, noise and heat, all of which play a key role in improving the working environment from a health and safety perspective. We recognize that, at the same time, our customers are looking for improved productivity and efficiency – and we believe that Sandvik is leading that race too.

We recognize that there can be perceived challenges – including infrastructure requirements, increased upfront capital cost and battery management/safety – but the gap is closing and the shift is accelerating, driven by sustainability, mine economics and operator health.

Building on its 40 years' experience of electrification, Sandvik has continued to acquire industry-leading competence and expertise in BEV technology, which we are keen to share with mining companies as they seek to assess the benefits and opportunities, wherever they are in the race. We firmly believe that mining companies should consider BEVs when planning their mine design and fleet strategy, and have worked with Partners in Performance to develop a number of purpose-built tools to help them evaluate the transition. Sandvik's specialist resources are, of course, always available to provide further guidance and support.

Mats Eriksson, President
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Partners in Performance

At Partners in Performance, our approach is grounded in our core values of simplicity and velocity.

By staying focused on the big picture and taking quick and practical steps to solve today's challenges, we believe we can all help build a better future.

This white paper exemplifies this philosophy as it explores an actionable pathway for mining companies to achieve sustainability goals, improve productivity, and enhance the quality of our work environment.

When we began this partnership with Sandvik, we asked a simple question: what tools can help underground miners unleash their potential now and have a lasting impact? This report not only answers this question, but also offers insights to help mining companies take bold, clear action to reduce harmful emissions.

We have reached a tipping point where underground Battery Electric Vehicles (BEVs) provide more than just environmental and air quality benefits – they are a way to increase efficiency and improve people's health, safety and working environment. BEVs make sense practically and financially. The business case for BEV adoption is stronger than ever, and the factors making them competitive will improve in the coming years.

Alongside Sandvik, we welcome the opportunity to assist mining companies in accelerating their journey to a cleaner world.

Brady Countryman, Director
Partners in Performance

Table of content

BEV refers to underground Battery Electric Vehicles throughout this document.

1. Introduction

“As many as one in three brownfield underground mines can expect to see a lower operating cash cost per tonne with BEVs vs. an ICE fleet already today.”

The global community has recognized the urgent need to decarbonize and limit global warming to 1.5 °C above pre-industrial levels. As per the 2015 Paris Agreement, more than 190 countries are committed to reducing greenhouse gas (GHG) emissions and companies are facing increasing scrutiny from customers, financial stakeholders and regulators in demonstrating a proactive response to climate change. Overall, this has triggered a worldwide energy transition away from fossil fuels and is having a profound impact in the way we use, generate, and transport energy – and the mining industry is equally engaged in this transformation.

In October 2021, the International Council of Metals and Mining (ICMM) announced its commitment to reach net zero greenhouse gas emissions by 2050 or sooner. This document was signed by all members, who collectively represent a third of the global mining industry. As a result, new technologies are being considered to support the execution of this mandate. Low-cost renewable energy and rapid improvements in battery technologies create opportunities for electrification and decarbonization within underground mine operations – in which underground Battery Electric Vehicles (referred to as BEVs throughout this document) are expected to play a key role.

In the case of the greenfield projects that are being undertaken today, the minimization of fossil fuel-based energy will be a driving factor in an operation’s viability – alongside other more typical considerations such as mine design, planning, and ore movement strategies.

As a result, mining corporations need to direct extra effort into their strategic and capital plans. Care should be taken to avoid project designs or fleet strategies which could prove costly in the long term – for example, a reactive redesign of mine plans, sell-off or write-off of older combustion engine technology and, at worst, stranded assets.

We suggest that there are three critical aspects mining companies should consider for their current and future underground mines (See Figure 1: Implementation framework):

1. **Assessment criteria** for mobile fleet selection, based on technical, productivity and financial metrics, as well as working environment, GHG emissions and social license to operate.
2. **Deployment process** for zero/low emissions equipment, including mine design optimization, development of the supporting infrastructure and operator/technician competencies.
3. **Management strategies** – both maintenance and operational, to support zero/low emissions equipment and associated assets and infrastructure (batteries, charging stations, etc.).

Given that BEV technology is rapidly evolving, a more agile approach is required beyond the traditional project design model that restricts solutions to long-standing and mature technologies.

At Sandvik and Partners in Performance, we believe that underground electric equipment will improve sustainability, working environment, license to operate and mine economics. For this reason, we have decided to collaborate and accelerate this transition by sharing our observations and learnings as pioneers within this industry space. This document presents various elements designed to support mining companies in assessing the opportunities that BEVs present for current and future underground operations, with a particular emphasis on hauling.

Figure 1: BEV fleet implementation framework

BEV Assessment

Technical Feasibility
— BEV specifications and performance
— Integration with mine design/operations
— Electrical infrastructure requirements

Economic Assessment
— Total cost of ownership
— Direct benefits (speed/productivity/labor, maintenance, energy regeneration)
— Indirect benefits (ventilation, cooling)

Health, Safety and Environment
— Reduction in DPM (diesel particulate matter) emissions, heat and noise levels
— Understanding net GHG impact
— Understanding/managing new risks

BEV Deployment

BEV Readiness Plan
— Project management
— Timeline for pilot/rollouts
— Synchronization/integration with diesel fleet strategy

Ramp-up
— Trials and troubleshooting
— Tracking of performance data
— OEM support

Skills and Capabilities
— Roles and responsibilities
— Recruitment processes
— Training program

BEV Management

Operating Strategies and Tactics
— SOPs and operational guides
— Review of performance metrics
— Charging philosophy and infrastructure

Battery Management
— Battery management plan
— Health and availability tracking
— End of life processes

Maintenance and Electrical
— BEV maintenance
— Electrical infrastructure management
— OEM support services

“BEVs are at a 'tipping point' with diesel mechanical equipment.”

A key element that will ultimately drive BEV adoption is economic feasibility. This document presents findings from our techno-economic modeling framework which incorporates variables ranging from equipment performance and productivity, capital and operating costs, and indirect costs such as ventilation, cooling, and carbon pricing. Our main findings are as follows:

- BEVs are at a ‘tipping point’ with Internal Combustion Engine (ICE) equipment: BEVs are generally competitive with ICE equipment (typically +15/-15% on a Total Cost of Ownership), not only for greenfield mines, but also for brownfield operations.
- As many as one in three brownfield underground mines could already expect to see a lower cash cost per tonne with BEVs vs. an ICE fleet, considering the potential for improved productivity (BEVs are faster, more powerful, and quicker to accelerate) in combination with fuel, maintenance, and ventilation savings.
- Designing for BEV in greenfield operations may lower Total Cost of Ownership by 10%–15% compared to a greenfield deployment of a traditional ICE fleet in some scenarios.
- Our model shows that one of the most significant cost drivers for BEV economic feasibility is battery costs. This highlights the critical importance of developing a clear understanding of hauling energy profiles, and optimizing for battery life through mine design, planning, and proper battery management practices.
- Many of the factors that make BEVs competitive are expected to further improve over the coming years. This includes rapid improvements in battery performance, durability, and cost, as well as stronger supporting policy frameworks for electrification.
- An attractive business case today is for flat level haulage on shorter routes (e.g., block caving mining, hauling from stope to ore pass, transport level truck loops) as this allows for the simplest BEV integration, minimizes logistical effort, and has a relatively low average power demand on batteries. Truck hauling on ramps has also proven attractive for BEVs, in particular for ramps < 5 km long and in mines that can capitalize on the opportunity to increase travel speeds.
- Upfront capital investment for electric machines and batteries remains higher than for conventional fleets, although this gap is expected to close over the coming years thanks to technology developments and manufacturing economies of scale. These initial higher fleet investment costs can be significantly offset by improvements in productivity, ventilation costs, and lower maintenance costs.

“Every mine has a capital purchase or a maintenance replacement coming up in the next few years, and they would be missing out if they decided not to investigate or pursue battery-electric technology.”

First out of the box – Solid Ground: Solid Ground New Afton [1]

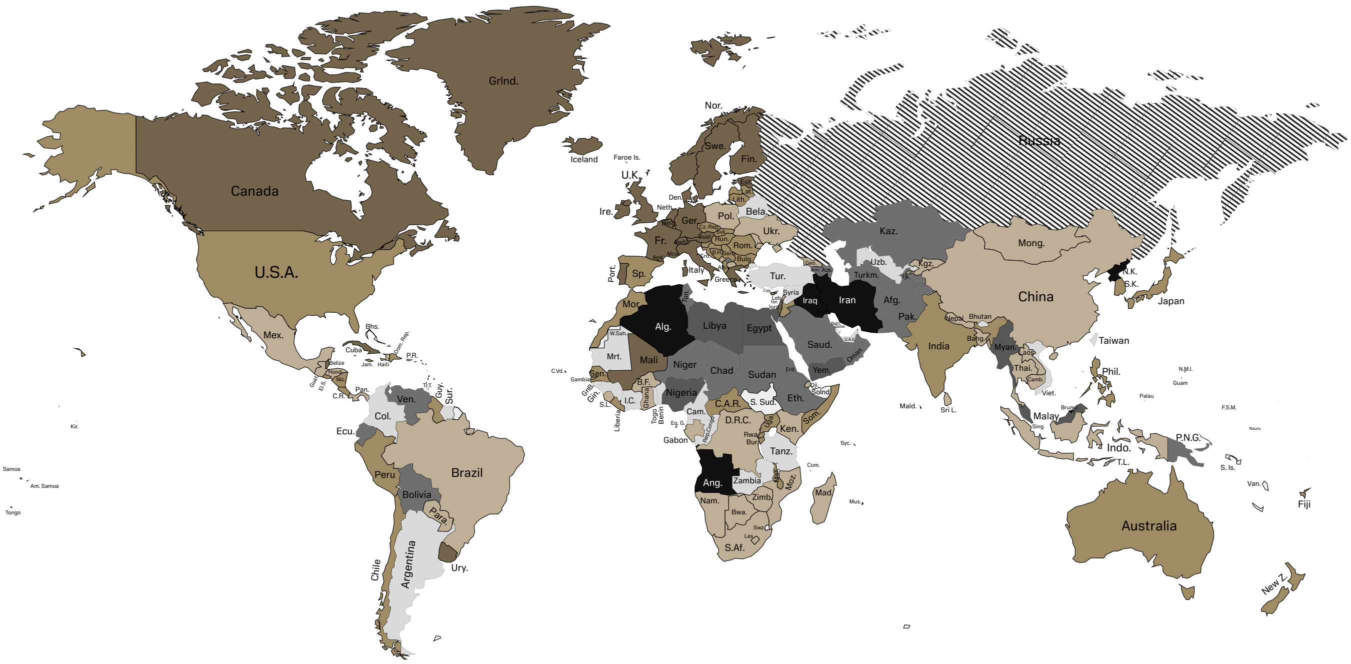
Jeff LaMarsh, Mine Superintendent at New Afton Mine, next to a Sandvik LH518B battery-electric loader.

1 First out of the Box – Solid Ground

Total Cost of Ownership (TCO) analysis has allowed us to pinpoint a diesel "cut-off" price in USD/L. In a typical haulage scenario, when the regional diesel price is higher than 1.2 USD/L, TCO over life of mine shifts in favor of BEV equipment.

By combining diesel and electricity prices with an index for ESG (Environmental, Social, and Governance) pressure (UN Sustainability Development Goals Ranking), we have created a "BEV Attractiveness Index" to illustrate where the conditions for BEV adoption are most favorable. Generally, the business case for BEVs will be the most attractive in countries with a high cost of diesel, a low cost of electricity, and more stringent ESG regulatory frameworks and requirements.

Figure 2: BEV attractiveness index for underground mines



Solid standalone business case even without indirect benefits
Standalone business case is inconclusive
Weak standalone business case, indirect benefits needed

% of underground hard rock mines

Standalone = machine-related cost per ton

Indirect benefits = for example ventilation, cooling, emission reductions

2. Background on BEV adoption

2.1 A brief history of underground electric vehicles

Despite the accelerated shift towards underground electrification in recent years, electric vehicles are not a novel technology in underground hard rock mining. In fact, electric machines have been demonstrating high levels of performance for cutting, drilling, loading, and hauling for decades. Some recent developments in BEV drilling technology are briefly discussed later in this section. Cable-tethered, trolley-assist, and auxiliary battery electric vehicles are already familiar to many miners: Sandvik's first electric equipment dates back to the 1970s.

Over the last few years, Original Equipment Manufacturers (OEMs) have gradually shifted focus to the development of BEVs, for reasons both external and intrinsic to the mining industry.

External factors include renewed interest in electric vehicles due to recent advances in Lithium Ion technology (various sub-chemistries exist and are presented in later sections) which now make BEVs competitive with ICE vehicles, a significant increase in battery manufacturing capacity which brings a decrease in battery costs, and the rapid emergence and availability of supporting electric components for mobile applications, such as motors and inverters.

Intrinsic factors to the mining industry include the search for more productive and economic solutions to mine complex and deep ore bodies, the ambition to develop flexible electric fleets that are not constrained by cables or fixed infrastructure, GHG emission reduction targets, and the need to provide safer working environments.

Sandvik's first electric loadera prototype was built in 1972 by Tamrock (later acquired by Sandvik)

2.2 Advantages and perceived disadvantages of BEVs

As the shift towards BEV continues to accelerate, mining companies need to understand the advantages and disadvantages of utilizing BEV in comparison to ICE machines.

Observed advantages of BEVs:
— Mine economics:
  - Increased productivity: shorter cycle times, increased muckpile performance
  - Lower operating costs: fewer parts, components and service interventions
  - Reduced ventilation and cooling costs.

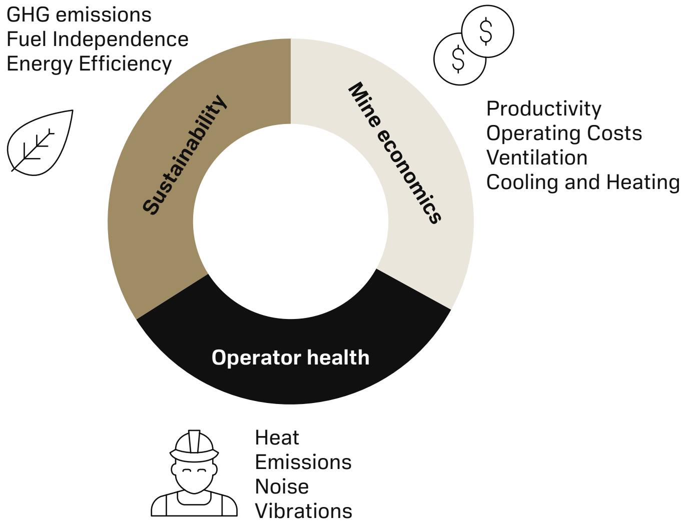
— Sustainability:
  - Reduction in GHG emissions
  - Fuel independence
  - Energy efficiency.

— Operator health and safety:
  - Reduction in diesel particulate matter emissions
  - Reduction in noise and vibration levels
  - Reduction in heat generation.

Perceived disadvantages of BEVs:
— Less flexible due to charging requirements
— Hauling range/distance limitations ("range anxiety")
— Uncertainty regarding battery life and end of life management
— Limitations in electrical infrastructure and power supply
— Battery safety concerns
— Need for new skills and competencies.

In this paper, these advantages and disadvantages have been explored and where possible, tested quantitatively through modelling and measurements. The transition to BEVs and their associated benefits and challenges also needs to be considered during the various phases of implementation: from initial assessment to deployment, and ultimately operations management.

Figure 3: Three main drivers to electrified mining



This is what operators are saying on BEV equipment:

On equipment performance:
"Plenty of power for bogging and tramming – no issues."
"Digs well, good for pushing stockpiles."
"Tramming speed is game changing."
"Range anxiety is a non-issue even after hundreds of battery swaps."

On working conditions:
"Working level a lot cooler."
"A lot less dust (no radiator fan blowing dust off the ground)."
"I feel much less tired after a working day."

2.3 Underground electric drills

This document primarily explores the economic and technical benefits of BEV equipment for ore hauling applications. However, a solution aligned with the industry's net zero goals will also require the electrification of other underground equipment, including drills and utility vehicles. Underground drilling has been partially electric for some time already. In most cases, modern drills are doing the actual drilling while grid connected, around 70% of the actual work. Recent developments in drill rig technology now also enable driving the machines on battery power and even doing some battery drilling. In this section, we briefly review the benefits and features of BEV drills as another example of how Battery Electric Vehicles can be integrated into mining operations.

Many of the benefits introduced by BEV haulage equipment apply equally to underground BEV drills: improved underground working conditions, lower environmental impact footprint and increased productivity:

- **Underground working conditions** are improved through a reduction in emissions, diesel particulates, heat, vibration, and noise
- **Lower environmental impact:** transitioning to BEV drills from diesel powered drills corresponds to a reduction of ~12 tonnes CO2e avoided per drill, per year, representing a reduction in diesel consumption of approximately 4,500 liters per drill, per year
- **Productivity improvements** through production, mine infrastructure and maintenance benefits. The following paragraphs describe some of the technical aspects of BEV drills which enable these improvements in productivity.

While models, designs, and technical specification may vary for underground BEVs, we describe here some features of Sandvik BEV drills that enable enhanced integration with mine operations and infrastructure, as well as productivity improvements.

Technical specifications
BEV drills will consist of an onboard battery pack, used for tramming and for peak-leveling services while grid-connected. The machines are equipped with onboard chargers which have been designed to be compatible with the existing mine power grid for use while the machine is drilling. This means that there are no additional power requirements when transitioning to BEV drilling technology, nor is there the need for infrastructure upgrades or charging infrastructure space allocation.

Generally, the majority of emissions and heat associated with underground drilling equipment are generated whenthe machine is tramming from one drilling location to another. With BEV drills, the machine trams on battery power, eliminating these tramming-associated emissions.

However, a battery powertrain requires mines to integrate into the equipment's battery cycle. BEV drills may be equipped with air cooling and inbuilt heating to aid battery temperature control, which prolongs battery life and improves machine performance.

Machines also use a single electric motor for both tramming and drilling functions, simplifying maintenance requirements, and reducing the volume of parts required over the life of the machine.

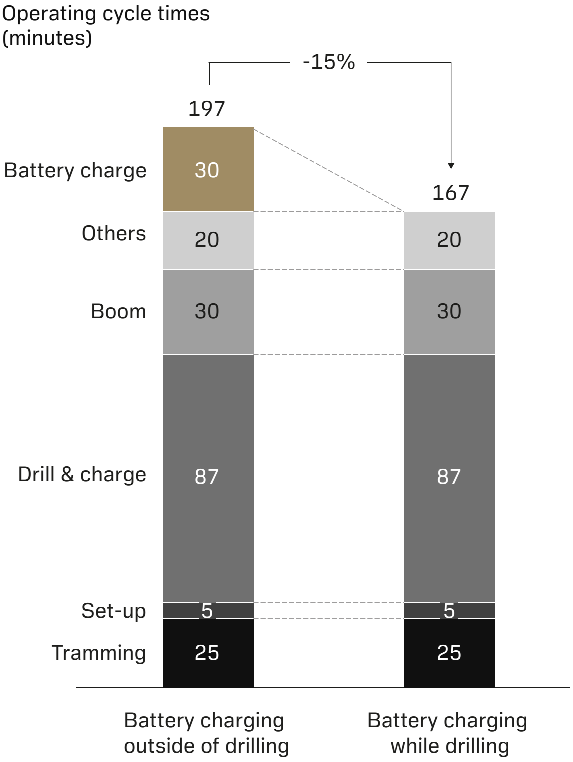
Also, the drills' multi-voltage capabilities allow for 380–1000V/50–60Hz input, enabling easy integration into most underground mining environments.

Sandvik DD422iE

Charging while drilling
Various technologies currently exist to facilitate battery charging for BEV drills; Sandvik utilizes patented intelligent charging control technology, enabling “Charging While Drilling”. The energy required for drilling comes directly from the existing mine power infrastructure, meaning no additional dedicated charging bays or infrastructure, or associated charging time. With Charging While Drilling capabilities, BEV drill productivity can be improved by up to 15% (compared to battery charging outside of drilling).

The following chart demonstrates the benefits of charging while drilling vs. charging outside of drilling.

Figure 4: Operating cycle with and without charging while drilling

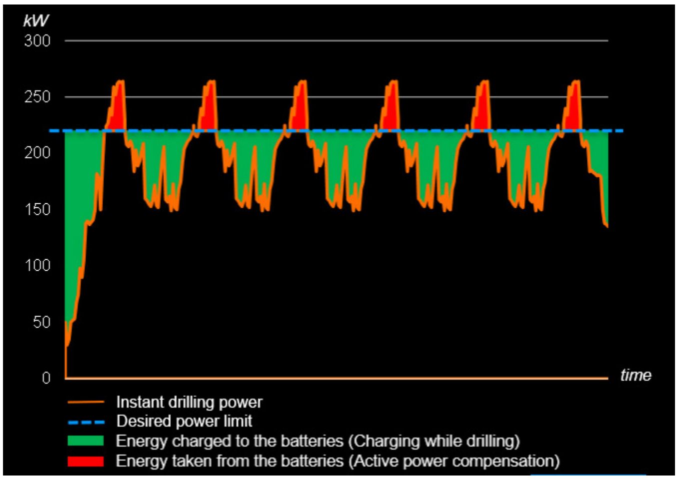


Active power compensation
Charging While Drilling technology, combined with active power compensation features, improves productivity, and can stabilize power fluctuations on the mine grid.

Active grid support can be utilized by defining the machine’s draw limit for current, which cannot be exceeded. If the electrical supply is weak, the unit’s battery can augment the grid supply and allow the machine to achieve full drilling power. A 20% reduction in peak power is possible when facilitated by Charging While Drilling.

Off-grid operation
Off-grid drilling & bolting makes it possible to drill and bolt in remote areas of the mine, where connection to the grid is not possible or practical. Up to 15–30 holes can be drilled relying only on battery power (note: this varies depending upon hole diameter, hole length and rock conditions). Drill activity can also be continued in the event of brief mine grid power outages.

Figure 5: Drilling cycle energy profile



Operational management
Several important elements should be considered when electrifying drills, including battery management and operating conditions. These are comparable to BEV haulage equipment and are discussed more broadly in later sections.

The overall transition of the full fleet to electric equipment (drilling, other auxiliary vehicles and hauling equipment) should be done through an integrated approach. For instance, an underground diesel infrastructure can be costly to establish and operate.

Diesel infrastructure
When a mine invests in electrification of the primary haulage fleet, the full benefit of removing risks and costs associated with operating a diesel supply infrastructure may not be realized until drills are also electrified. The rest of the document explores those factors for BEV hauling.

3. Technical feasibility

This section focuses on the key factors that mining teams should consider when evaluating the technical feasibility of hauling BEVs for their current or future mining hauling operations. These components can be summarized by the following:

— Technology integration with proposed mining plans or existing footprint/infrastructure (section 3.1)
— Equipment capabilities and specifications (section 3.2)
— Ventilation, cooling, and heating (section 3.3)
— Energy & power strategy (i.e. sourcing, and distribution, section 3.4)
— Energy efficiency and GHG emissions (section 3.5).

3.1 Technology integration with mining plans

Various technologies beyond mobile equipment exist to move ore from the working face to the surface. Non-hauling solutions in current underground operations include conveyors, trains, hoist shafts, pipeline crushers, and slurry pipelines; hauling solutions include load haul dumpers (sometimes referred to as loaders or LHDs) and trucks, which can even be supported by trolley assist systems.

The goal of the mine design team is to select from these available technologies and develop an optimal underground material movement strategy – not only from a value creation perspective, but also considering social license to operate and sustainability. In some instances, non-hauling solutions may be competitive or superior to mobile hauling, and in other cases it may make sense to combine several ore movement methods. In most applications, hauling trucks or LHDs are required to move blasted rock from the face to the next ore movement system.

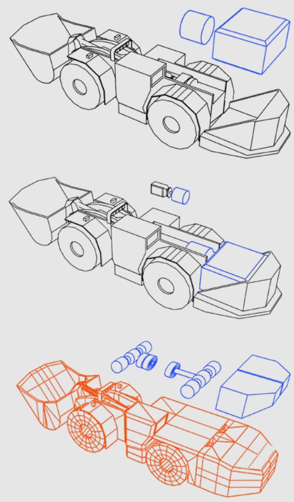
This initial technology mapping can now be augmented with BEV hauling solutions. For instance, an alternative to diesel incline hauling may include BEVs hauling to an underground hoist shaft or conveyor; BEVs may also allow for deeper excavation for vertical ore movement devices that may previously have been uneconomical with conventional equipment.

The generations of BEV
In terms of "pure" physical equipment performance and specifications (e.g., dimensions, weight, capacities, speeds, acceleration, turning radius), BEVs are on par with, or superior to, ICE mechanical equipment, thanks to continuous improvement in technology over the past several years.

First generation BEVs involved retrofitting ICE mechanical equipment by removing the internal combustion engine and integrating on-board batteries and electric drives, which came with limited performance improvements.

Second generation BEVs add an additional motor to drive hydraulics, which allows the removal of the torque converter, a reduction in hydraulic systems, and an improvement in regenerative braking.

Third generation BEVs are comprised of a bottom-up design tailored to a battery-powered electric driveline: as a result, there is no transmission and the frame has been re-engineered to maximize power output, deliver higher speeds and performance, and allow for smaller machines with larger capacity. This dramatically reduces the number of moving parts and can lower overall mechanical maintenance costs by 20%–40%.



3.2 Equipment capabilities and specifications

While BEV performance continues to improve with every new generation, a key area where BEVs prove advantageous is in terms of speed against grade performance. The primary reason for this difference is that electric drives can deliver nearly instantaneous high torques across a wide range of speeds, whereas the maximum torque with ICE equipment is only achieved for a narrow operating window. In the case of electric loaders, in addition to higher speeds, more power and improved torque control allows for more efficient, smoother, and faster muckpile performance which lowers cycle times and increases productivity, resulting in less wear on the machine and tires.

An additional key advantage is the split motor system in BEV equipment. Separate motors drive the traction and hydraulic systems, increasing the power available to each system. Traditional combustion engines powers both traction and hydraulics with each competing for available power.

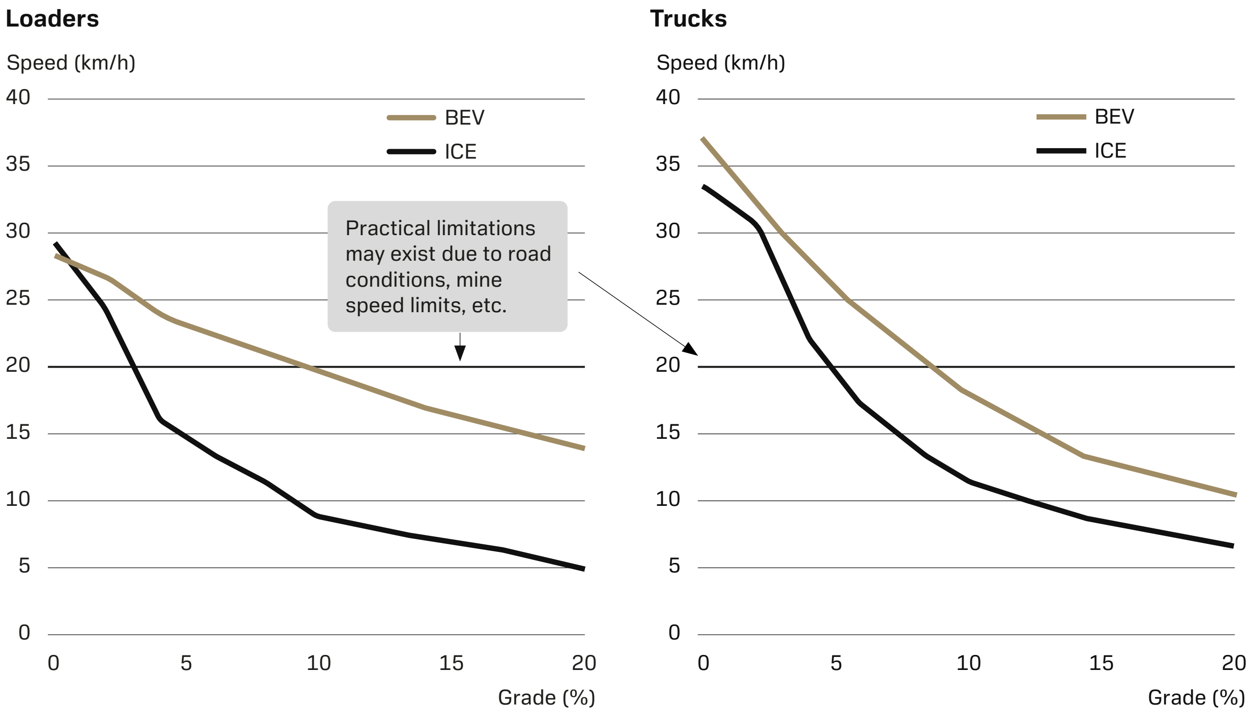
Finally, miners should consider the various solutions that are available to swap batteries. Current technologies include on-board or off-board charging.

Onboard charging reduces handling and limits the size of the battery fleet, but could potentially cause production delays and usually involves higher battery charge rates which may reduce useful battery life, and may also require increased electrical infrastructure capabilities to support higher charging rates.

Off-board charging may be achieved utilizing crane or fork-lift-assisted battery swapping, or self-swapping systems. In the case of crane-assisted battery swapping, cranes require additional labor to operate and increased planning would be necessary should the charge bay need to be relocated to a different area. Additionally, frequent swapping or battery maneuvering with the use of cranes introduces safety risks. Self-swapping batteries can typically be changed by the vehicle operator from the cabin in under 10 minutes, leading to a reduction in non-productive time resulting from battery handling and management. With improvements in technology and processes, battery swap times can now take closer to 6 minutes.

Figure 6: BEV comparison to ICE performance when loaded

✓ More power ✓ Up to 2x speed ✓ 60% faster acceleration ✓ 25% faster load time



Note: Highest gear used for diesel speed comparison LH58iB vs. 17t diesel LHD, TH550B vs. 51t diesel truck

"An ICE fleet typically represents 30–50% of heat generation in an underground mine. Converting to an electric fleet will reduce heat emissions by up to 80–90%. Together with the reduction in air particle emissions, ventilation requirements can be substantially relaxed."

3.3 Ventilation, cooling, and heating

A notable indirect benefit of BEV fleets is the reduction in ventilation. An ICE fleet typically represents 30–50% of heat generation in an underground mine. Converting to an electric fleet can reduce fleet heat generation by up to 80–90%. Together with the reduction in air particle emissions, ventilation requirements can be substantially relaxed. This results in lower capital and operating costs given that ventilation is one of the primary uses of electric power in a mine, generally accounting for 40%–50%[2] of electricity use.

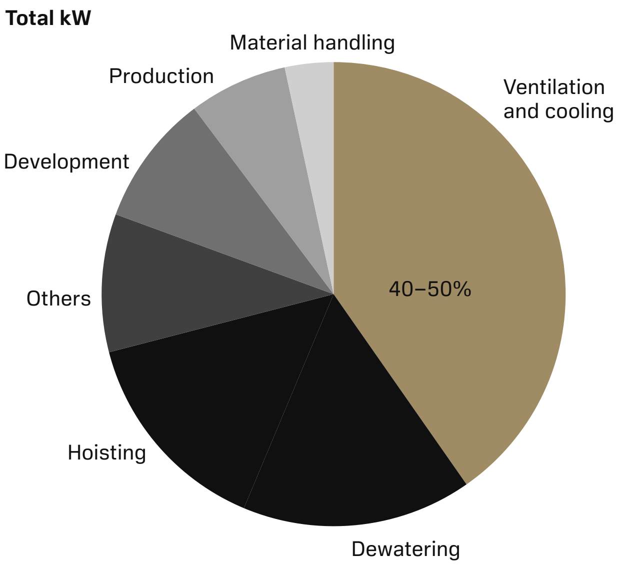
Ventilation requirements are driven by the need to dissipate hazardous residual blast gases, ICE fleet exhaust, and to assist temperature conditioning due to heat from fleet losses, fixed electrical infrastructure losses, rock auto-compression, strata heat, broken rock, and fissure water.

Ventilation and cooling system design is typically supported by underground heat and ventilation simulations to ensure sufficient and safe flows of air in all sections of the mine. Typical inputs to these models include:

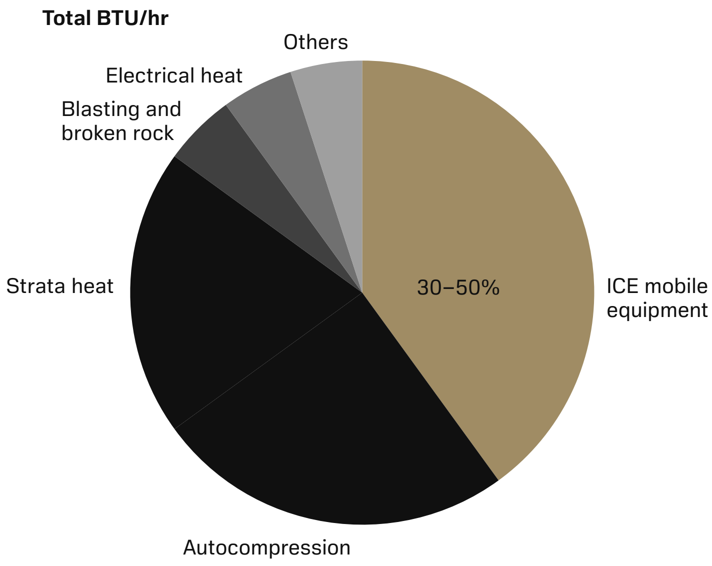
— Mobile equipment: exhaust heat, diesel particulate matter
— Heat from operating activities: shotcreting, blasting, broken rock, etc.
— Electrical equipment: heat losses
— Rock properties such as conductivity, diffusivity, specific heat, density
— Surface conditions: temperature, humidity.

Figure 7: Typical mine power demand sources and mine heat sources

Typical mine power demand with ICE equipment



Typical sources of underground mine heat generation



2 Nyqvist, J & Serres, M. (2020). ABB Discusses the advantages of Ventilation on Demand. p.37–40

One driver for the reduction in ventilation requirements is the reduction in heat generated: that BEVs use energy stored in the batteries at 80%–90% efficiency when performing work, whereas with ICE equipment, only 20–30% of the fuel energy (diesel) is converted to actual work, the rest being lost to heat. Energy efficiencies and heat losses are further detailed in GMG's 2018 paper "Recommended practices for Battery Electric vehicles in underground mining".

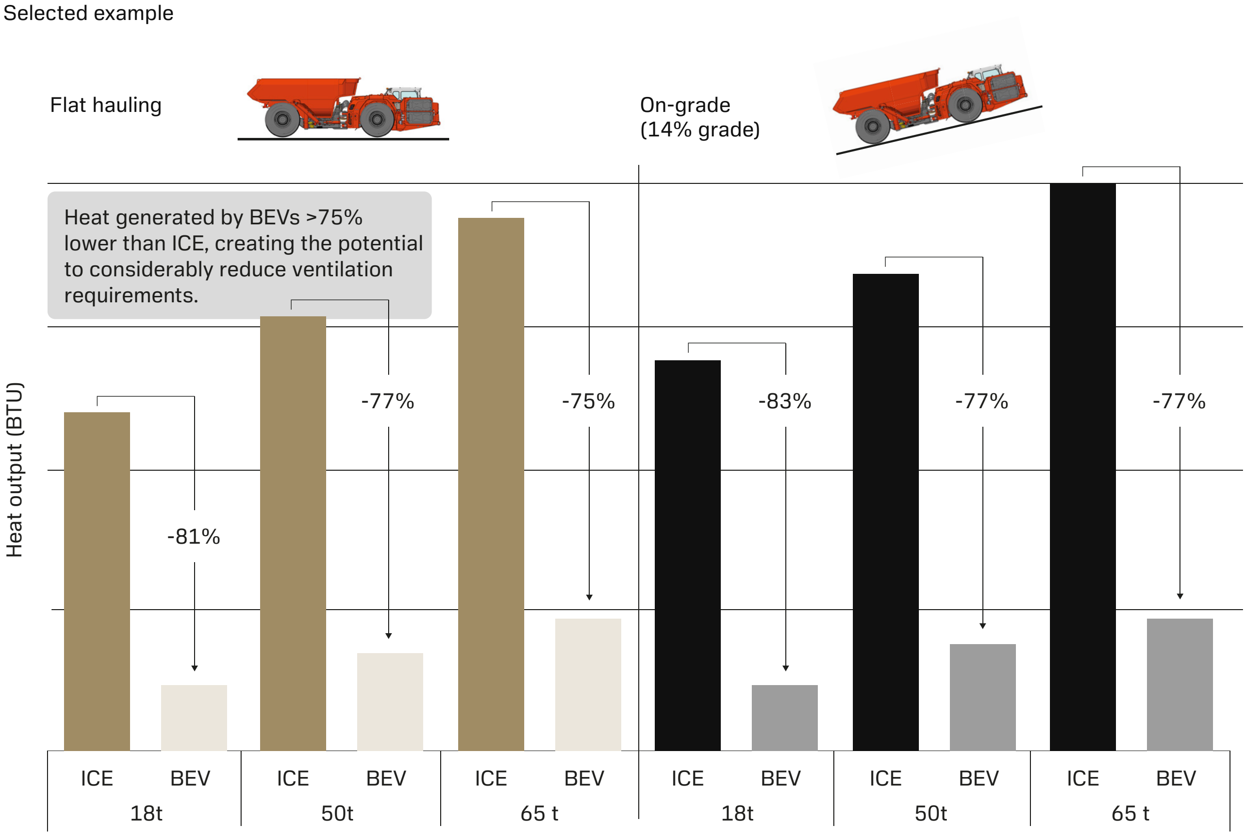
Another critical aspect of heat reduction and overall haulage efficiency is the ability to recapture gravitational potential energy from ascending a ramp through regenerative braking. While heat generation can be reduced by about 80% from ICE to BEV when solely considering drivetrain efficiencies, the additional energy capture through regenerative breaking allows close to 90% heat reduction in the case of an upramp hauling scenario[3].

Loaders also benefit from the removal of torque converters and the elimination of related driveline losses. Total reduction in heat/efficiency improvement is dependent on the proportion of time spent mucking vs. hauling.

In addition to reduction in ventilation requirements, a BEV fleet can also reduce refrigeration requirements when the mine requires additional cooling due to high operating temperatures. Conversely, BEV fleets can also enable a reduction in heating for cold climates as lower volumes of air have to be moved to displace diesel emissions, which in turns means the mine can be maintained at a certain operating temperature with lower levels of heating. In summary, lower air volumes lower the cost associated with cooling or heating energy.

Figure 8: Heat generation – ICE vs. BEV

Selected example



Note: This chart does not account for regenerative breaking, which may improve thermal efficiencies by 5–15% depending on cycle parameters.

3 "Heat generation in battery electric underground haul trucks." Artisan Vehicle Systems, Inc. 2018. 1–11.

We have seen that BEVs can substantially reduce ventilation requirements. It should also be noted that any reduction in ventilation requirements has compounding effects. Fan affinity laws explain that energy usage scales to the third power of airflow requirements. For instance, a 50 % reduction in airflow would result in 87.5 % reduction in energy usage. This also directly reduces capital costs when the design of ventilation systems is optimized with these lower requirements.

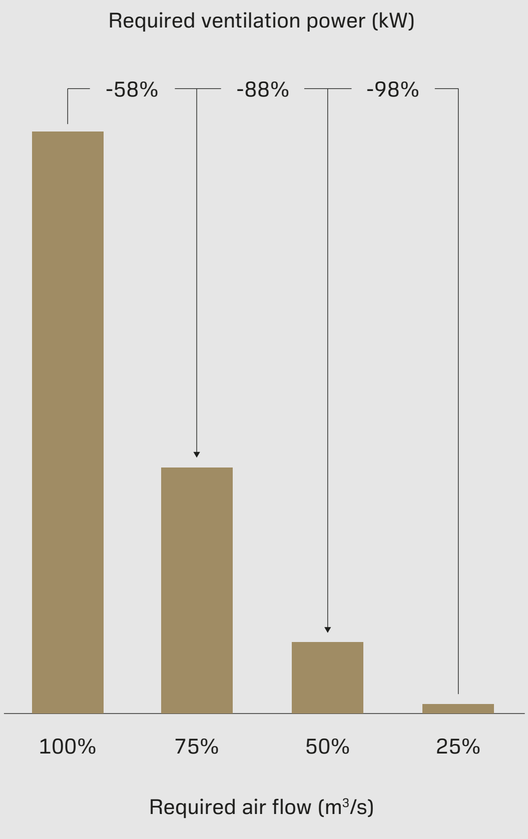
In addition to ore movement strategy and ventilation infrastructure planning, mine design teams must consider the additional development, footprint, and logistics required to support BEVs, such as battery charging bays and related charging infrastructure, underground workshops, parking bays, and battery movement strategies. This is discussed further in sections 6 and 7.

Fan affinity laws
the Affinity Laws for fans help to express the influence on revolution speeds, pressure and power consumption due to a change in volume flow requirements:

1. Volume Flow is linearly proportional to fan rotational speed
2. Pressure is proportional to the square of fan rotational speed
3. Power is proportional to the cube of fan rotational speed (and its volume flow).

This physical phenomenon explains how even relatively modest reductions in ventilation requirements can have a fairly large impact on ventilation operating and capital costs.

Figure 9: Fan power vs. required air flows



3.4 Energy and power strategy

Electrical distribution is a key consideration in underground operations, and any potential incremental load imposed by BEVs should be considered early in mine electrical infrastructure design. It is important to begin by understanding how vehicle and battery cycle times have an effect on mine power demand.

Aside from the number and models of BEVs comprising the fleet, several other factors will drive total instantaneous and average power demand, such as charging philosophy and flexibility requirements (e.g., number of extra batteries per vehicle).

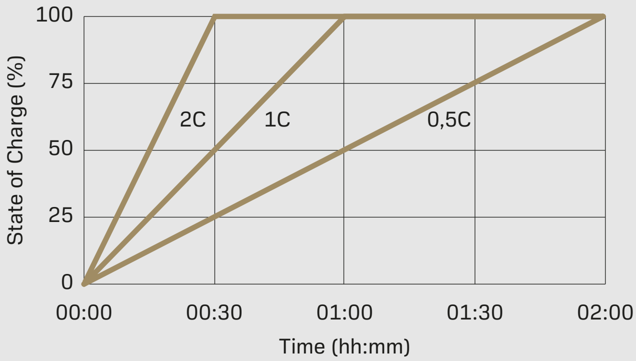
Charging philosophy, in particular, relates to the speed of battery charging and is typically reflected in the configured C-rate (see pop-out box).

Understanding battery C-rates
C-rate is a proportion of the capacity (C for Capacity). It measures the rate at which a battery is being charged or discharged, and is defined as the current through the battery divided by the theoretical current draw under which the battery would deliver its nominal rated capacity in one hour.

Example:
2C is twice the capacity in amps, for a 1/2 hour rate.

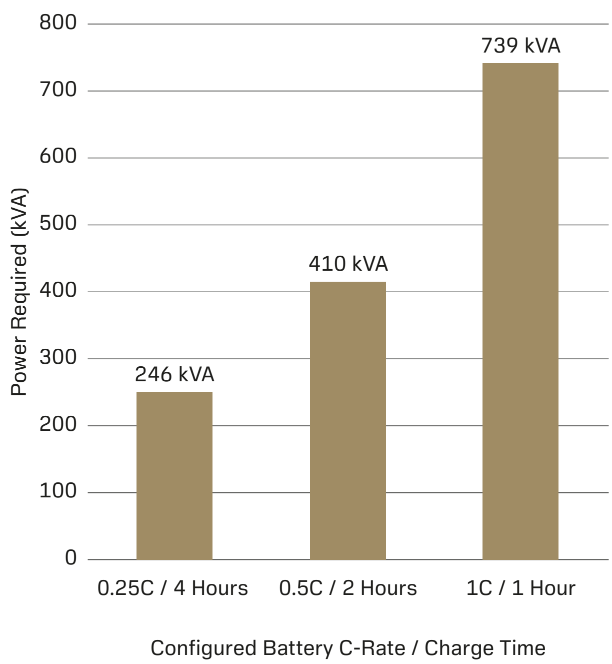
A 1C C-rating corresponds to the current required to fully charge (or discharge) a battery in one hour.

A 0.5C rating corresponds to the current required to fully charge (or discharge) a battery in two hours.



Operations may be inclined to favor faster charging rates, as they would appear to minimize any unproductive time driven by battery charging. However, the disadvantages of fast charging include increased battery heat generation, accelerated battery capacity degradation, and an increased risk of thermal-related hazards. Due to the higher currents required at fast charging rates, energy costs will be also higher (given that electrical losses are proportional to the square of current). Additionally, fast charging drives higher instantaneous power demand, which may not be able to be supported by existing mine infrastructure, or would necessitate larger or more complex electrical equipment (cabling, switchgear, substations, and other distribution components). Fast charging could also increase overall electricity costs, through power demand “peaks” above contractual capacity allowances.

Figure 10: An example of power input requirements of various charging rates for one Sandvik charging system (2 chargers and 1 cooler)



*Assumes 600V input with standard cable losses

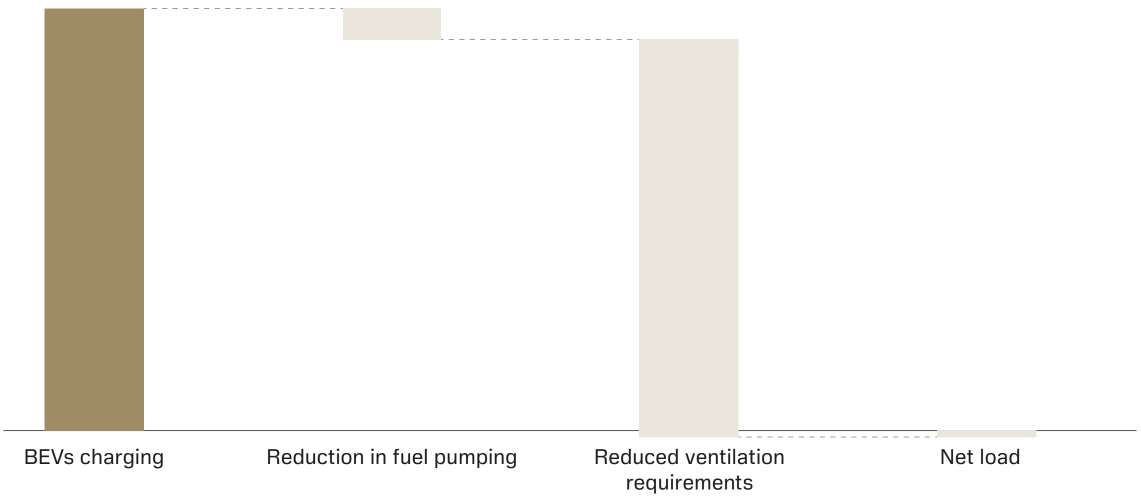
For these reasons, lower charging rates are generally recommended, and this can be optimized through haul route design, rightsizing of the battery fleet (typically one spare battery for every 3 BEV) and location of recharge bays. It is important to note that fast charging doesn't necessarily increase overall fleet productivity, particularly in a battery swapping system where multiple batteries are being used. For instance, if a truck battery can sustain three hours' runtime over a typical cycle, it is recommended that the paired battery should be configured to charge in three hours to maximize charge time without impeding production.

When optimized, we have found that the introduction of BEVs may be power-neutral at charging rates given the reduction in ventilation and cooling power requirements. This is an important finding, as it means BEVs may not necessitate large, if any, upgrades to power systems. However, a distinction should be made as to the distribution of power. Primary fan power will be on the surface whereas charge power (and secondary ventilation) will be needed underground.

Figure 11: Net increase in electrical load when transitioning from an ICE Fleet to BEV Fleet

MW

Selected case study



When optimized, we have found that the introduction of BEVs may be power-neutral given the reduction in ventilation and cooling power requirements.

In any event, a load forecast is key to developing an overall optimization of electrical systems, and should be conducted in order to ensure a safe and efficient operation, and reduce costs. Levers available to mining electrical teams to optimize underground electrical systems may include the choice of distribution voltages, sizing of transformers, switchgear, and electrical distribution cables.

Finally, the incremental electrical demand from BEVs should be integrated in the overall site power sourcing strategy. An optimal power strategy considers overall site energy requirements, average power and peak demand and aims to lower the total cost of electricity, providing operational reliability, flexibility, and lowering carbon footprint. A combination of onsite renewables and commercially sourced renewable electricity for grid connected sites can enable companies to decarbonize their power supply.

3.5 Energy efficiency and GHG emissions

Generally, we find BEV hauling is more energy efficient than ICE mechanical hauling, even accounting for lower specific energy of batteries vs. diesel (energy per kg), and this is key for mining operations where a significant portion of consumed energy at site is directed to ore haulage. BEV hauling can enable an energy intensity per tonne three to five times lower than diesel ICE hauling.

Similarly, transitioning to a BEV fleet generally results in a significant net reduction in GHG emissions. Interestingly, we have found this may be the case **regardless of how they are charged** (i.e., the power supply generation sources and the carbon intensity of power supply). This result is driven by the reduction in energy and emissions associated with ventilation and cooling. This result differs from on-road vehicles where a carbon intensive power supply may result in an increase in GHG emissions. In other words, even if heavy fuel oil or coal is used to generate the electricity used to charge BEVs, the reduction in emissions associated with ventilation energy may offset the increase in emissions from BEV charging.

Figure 12: Mining energy intensity

MJ/tonne, including ventilation and cooling
by energy type
Selected case study

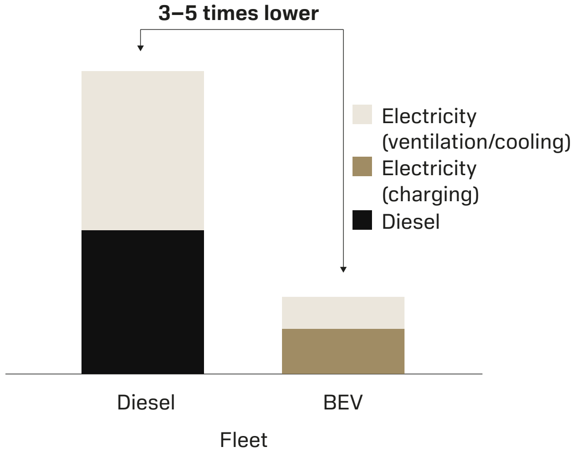
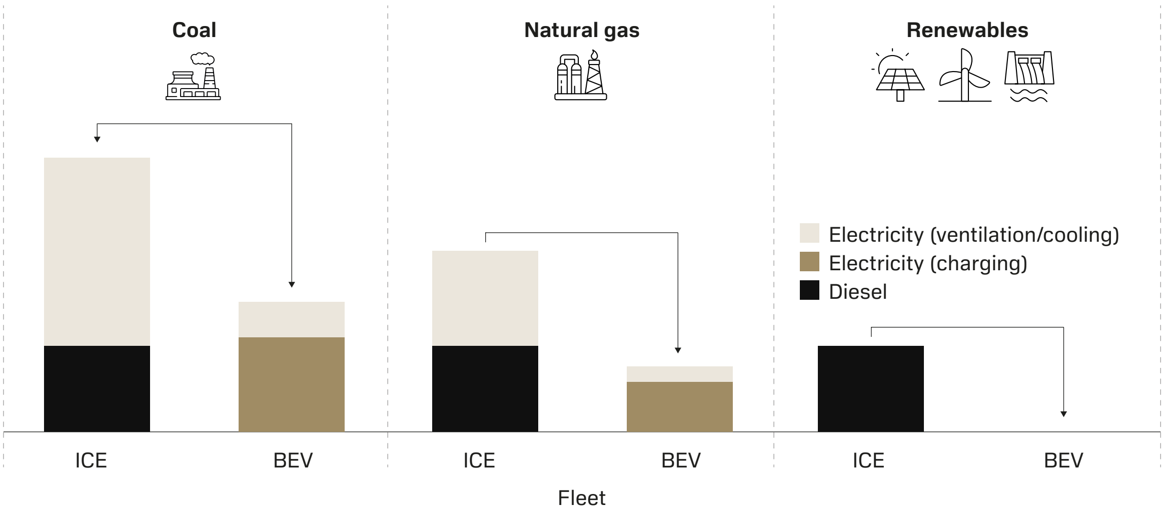


Figure 13: Mining emission intensity by power supply type

tCO2e/tonne, including ventilation and cooling
By type of power supply
Selected case study



Obviously, the largest emission reduction is achieved when a BEV fleet is paired with renewable energy sources. This configuration is becoming more popular within the mining industry, with mining companies securing renewable power generation for their sites.

As mining companies continue to assess and implement changes in their fleet and energy strategy (scope 1 and 2 emissions), additional consideration should also be given to understanding the overall full value chain impact of these decisions by factoring in the carbon footprint associated with the production of their fleets, power infrastructure and energy (scope 3 emissions).

Renewable microgrids in mining

One particularly interesting trend is mining companies investing in local renewable power generation for mine sites. Wind, solar, and hydro projects are being executed all over the world with significant size and generation capacity. These mines will not only be able to power their fleets with carbon-neutral energy, but also reduce dependency on a central grid for power supply and international supply chains for fuel imports.

One example is Gold Fields, who in 2021 initiated the construction of a 50MW Solar Plant for its South Deep mine in South Africa, and is also concurrently trialing a BEV fleet. The solar plant is expected to generate approximately 20% of the electricity consumption of the mine and reduce around 100,000 tonnes of CO2e emissions annually. With electricity making up about 13 % of the total operating cost for the mine, the solar microgrid is expected to improve both reliability and cost of electricity.

When combined with stationary energy storage (possibly including “end of life” batteries from mobile fleet) to supplement power scarcity periods (e.g., overnight, during low wind conditions, or during poor weather), mine have the opportunity to revolutionize how they obtain and use electricity.

When an operator opts for an off-board strategy (e.g., battery self-swapping), there is always a fleet of batteries connected to grid-tie inverters. Those batteries can be used for buffering renewables/peak saving/frequency regulation even excluding second life batteries.

Combining renewable microgrids with battery fleets and second life batteries might prove to be a successful way for mines around the world to ensure stable, green, and cost-efficient supply of power.

4. Business Case

4.1 Key findings

Aside from the benefits that BEVs provide, the speed of their adoption will ultimately be driven by economic feasibility. In this section, we present various elements that drive the economics of BEVs, measured by their associated Total Cost of Ownership (TCO) and compare the results with ICE equipment.

In many cases, BEVs are already proving economically competitive to ICE equipment. While economics are highly dependent on mine-level variables such as local electricity cost, diesel cost, mining method, and ore body geometry (hauling profiles and ventilation constraints), TCO modeling demonstrates that BEVs may be competitive with ICE in many types of greenfield and brownfield settings and scenarios, including flat, downramp, and upramp hauling.

Additionally, most of the factors that lead to current BEV feasibility are expected to become more favorable as technology develops and adoption increases. These include:

- **Model availability** – OEMs are quickly moving towards covering all popular size classes
- **Equipment performance and reliability** – experience and learnings from the field will lead to fine tuning and optimization of equipment design and features
- **Equipment capital costs** – the rapid increase in demand and subsequent increase in production and supply will yield benefits associated with economies of scale
- **Batteries** – improvement in performance and decrease in costs can be expected with the scaling up of primary supply, investment in battery manufacturing capacity, and secondary recycling market
- **Cost of electricity** – expected to come down with increased supply of low cost, low carbon/renewable power
- **Cost of fossil fuels** – highly volatile in nature, sensitive to geopolitics and becoming more costly in jurisdictions favoring decarbonization (in part due to removal of tax breaks)
- **Cost of ventilation, cooling and heating** – mines digging deeper into ventilation-constrained areas will experience increasing costs to maintain an acceptable working environment
- **Carbon pricing** schemes are being adopted globally and prices of carbon are trending up.

Figure 14: EU Carbon Permits Costs (EUR)

4

There is a case for early adoption over a "watch and see" or "fast follower" approach. The experimental pioneering phase for the technology has ended, and we believe most miners should consider electrification. Investing in BEV equipment during the early adoption phase allows operators to gain experience, inform future mine design/planning decisions, and ultimately better capture the economic benefits from widespread adoption.

Additionally, at the time of writing this paper, inflation, supply chain constraints, and lead times in securing BEVs may provide additional reasons to favor a faster design and procurement strategy. Early-phased adoption also often allows for the careful development of operating and safety procedures, leading to better management and planning of any potential risks (see Chapter 5. BEV safety).

4 EU Carbon Permits - 2022 Data - 2005-2021 Historical - 2023 Forecast - Price – Quote. Tradingeconomics.com

4.2 Business case drivers

A TCO assessment should be conducted in order to understand the economic feasibility of BEVs for specific mining operations, considering several drivers. Table 1 lists the main elements affecting productivity, operating, and capital costs as relating to BEVs. Some of the more salient benefits of BEVs over ICE equipment include:

Production

— **Cycle times:** The electric drives in BEVs can deliver near constant power in a range of different speeds, whereas diesel engines typically only operate in a small window of peak power. This means high torques at low speeds for BEVs, resulting in higher acceleration and overall higher operating speeds.

— **Muck-pile performance:** The increased tractive force also increases muck-pile performance where fewer passes are required to fill a loader bucket.

— **Fleet scalability:** In ventilation-constrained contexts, more BEV units may operate without adding significant ventilation requirements that would otherwise be introduced with ICE equipment.

Capital costs

— **Ventilation and cooling systems** are typically sized to evacuate excess heat and Diesel Particulate Matter (DPM) generated from the use of diesel equipment. With lower heat generated by BEVs and the absence of DPM emissions, the associated capital and operating cost savings (energy and demand charges) due to the reduction of ventilation demand can be substantial (fewer/smaller ventilation shafts/fans, access drifts). This benefit is not only true for greenfield projects, but also for brownfield operations by deferring or avoiding ventilation and cooling infrastructure investments.

— **Elimination of diesel infrastructure costs**, which can typically include fuel logistics, storage and distribution systems.

Operating costs

— **BEV hourly parts and component costs** may be reduced by 20–30 %, and in some applications as much as 40 % compared to that of ICE equipment, driven by the high reliability of electrical systems and the absence of an engine, exhaust system, radiator, central transmission system, torque converter, reduced filters and hydraulic oils, and overall fewer moving parts. Additionally, intelligent embedded sensors can enable proactive and predictive maintenance.

— **Regenerative braking** allows the recovery of electrical energy when travelling down ramp. Onboard Battery Management System (BMS) allow an efficient use of energy throughout a hauling cycle.

Table 1: Direct and indirect benefits/costs for BEV vs ICE

		Direct benefits (+)/costs (-)	Indirect benefits (+)/costs (-)
Total Cost of Ownership BEV vs ICE	**Production**	+ Lower cycle times: higher acceleration and speeds + Potential for higher availability due to fewer moving parts and less time in service	+ Crew productivity gains from improved air quality, lower temperature, and noise levels
	Capital	+ Opportunity to reduce fleet size through higher productivity (can also reduce congestion) - Higher capital costs for BEVs + batteries	+ Mine development cost optimization + Reduced ventilation and cooling infrastructure + No need for diesel handling infrastructure - Electrical infrastructure upgrades
	Operating	+ Mechanical routine and rebuild maintenance costs (parts and labor) given fewer moving parts + Lower maintenance labor costs with simpler driveline maintenance + No diesel costs + Regenerative braking recovers electrical energy - Electricity energy costs to charge batteries - Battery service costs - Battery charging infrastructure and technicians	+ Reduced ventilation, cooling and heating energy requirements and operating costs (brownfields and greenfields) + No diesel logistics + Reduced carbon costs when applicable

"**+**" refers to benefits of selecting BEV instead of ICE i.e., regarding productivity and maintenance.
"**-**" refers to added costs of selecting BEV vs ICE i.e., battery charging infrastructure and capital investment of batteries.

4.3 Individual cost drivers

The business case for BEVs will vary based on mine design and hauling profiles. For a typical mixed or upramp hauling operation, BEVs are already expected to be competitive, if not more attractive, than ICE mechanical equipment.

The following chart (Figure 15) shows comparative mine life TCO for BEV and ICE in this upramp-hauling scenario, assuming a certain life of mine production objective. It is key to note that this is on a pure cost basis comparison only, and that important additional benefits could be unlocked when the operation is hauling constrained, either because of congestion or ventilation constraints, through additional production.

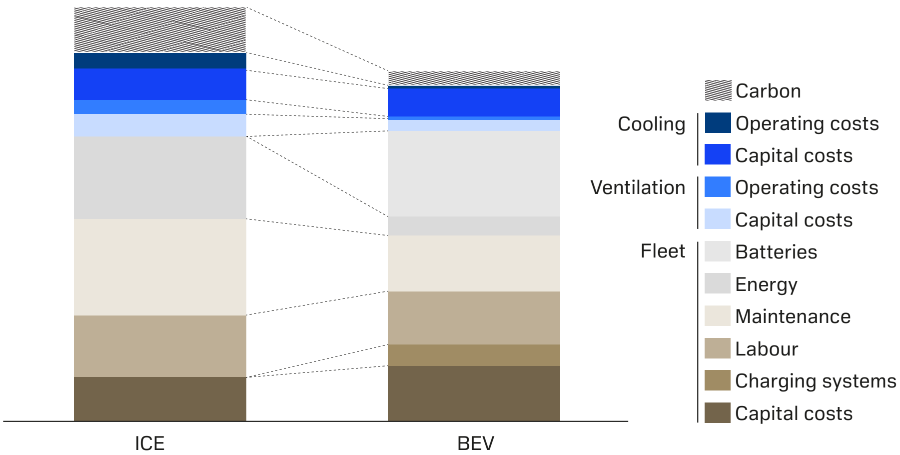
In this scenario, BEVs are competitive with ICE Equipment, even in the absence of carbon costs and ventilation/cooling benefits. BEVs also enable lower maintenance but are partially offset with higher capital costs, and the largest spend is concentrated in battery usage. Operators may decide to make battery costs a capital expense through upfront purchases of batteries, or to opt for a battery rental option as an operating expense. The latter may also come with ancillary benefits (e.g., capacity guarantees, service, end of life management provided by OEM). The decision to pursue battery ownership vs. rental should be carefully evaluated by considering economics, risks, and operating systems in place to support battery fleet health.

In any event, it is important to understand the drivers of battery costs, which are ultimately driven by cumulative usage; or in other words, battery charge and discharge cycles. This may be interpreted as average battery power over a hauling cycle.

To further understand the other cost drivers and their relative impact to BEVs, Figure 16 presents the sensitivity to the business case for BEVs to key site techno-economic variables.

Figure 15: Total cost of ownership

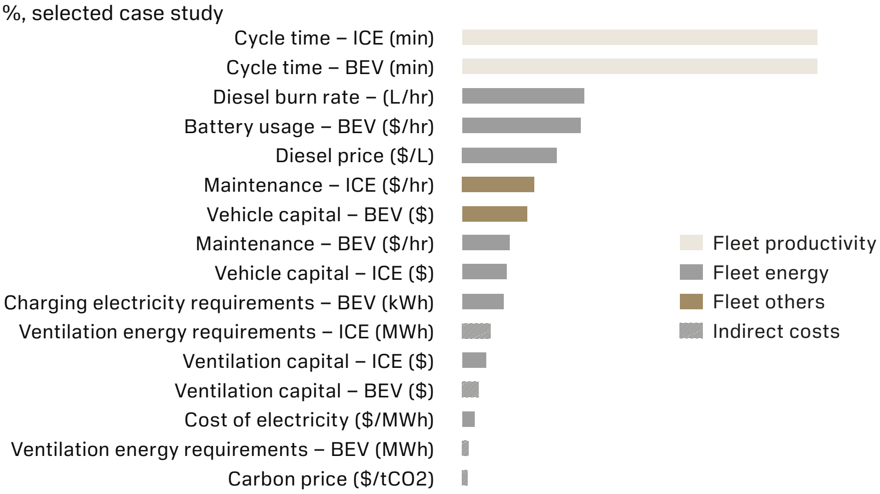
Net Present cost, $, Selected upramp scenario



Note: vehicle maintenance excludes battery maintenance

Figure 16: Sensitivity analysis

%, selected case study



In addition to battery costs and average battery power, the other major key lever in the business case for BEVs is fleet productivity. BEVs benefit from faster acceleration and speed on upramp profiles.

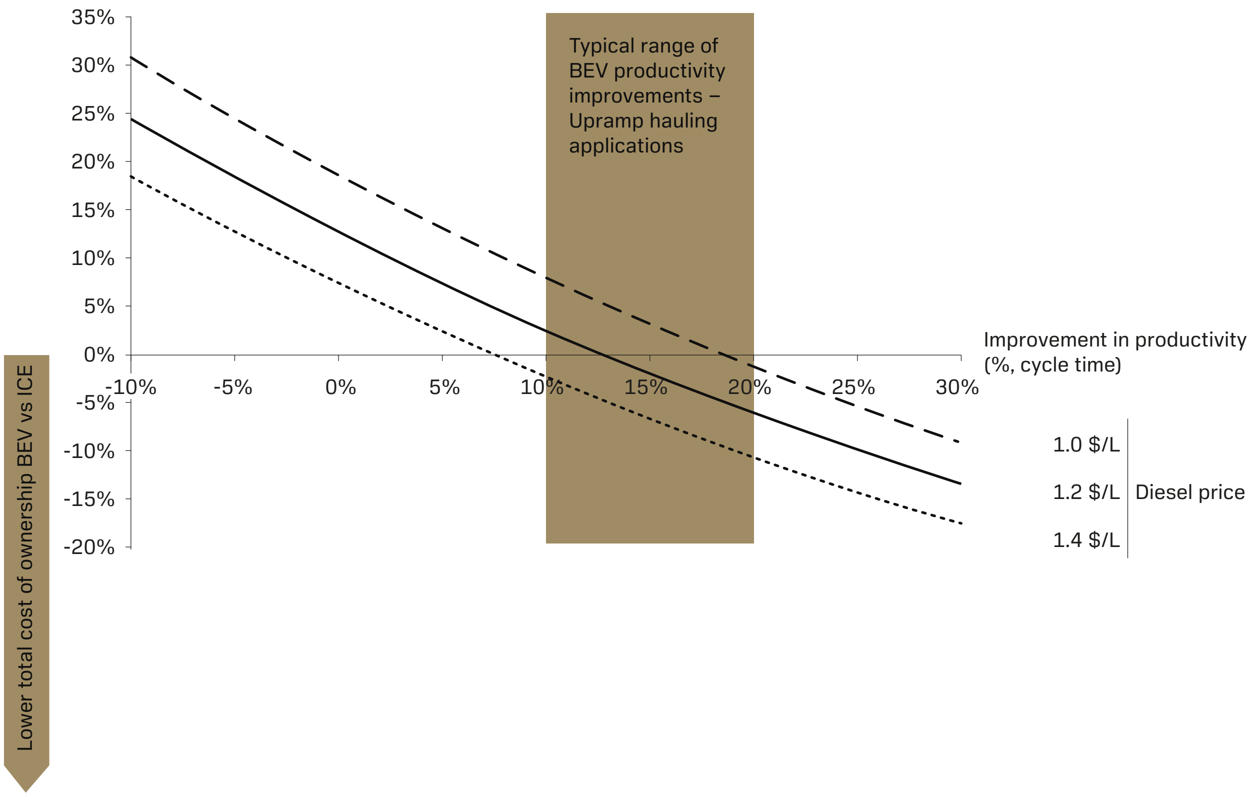
As Figure 17 demonstrates, the business case for BEV (as measured by premium vs ICE fleet) is strengthened by relative productivity improvements in hauling cycles. For example, a mine with a diesel cost of 1.2 USD / liter that achieves 10–15 % cycle time improvement with BEVs, is expected to realize an equivalent cost per ton to an ICE fleet already today, on a pure fleet by fleet cost comparison. Indirect benefits like ventilation savings, work environment improvements and reduction of carbon emissions will come on top of this as additional payback.

The significance of productivity and energy usage metrics emphasizes the importance of developing site-specific hauling models to better understand and optimize the business case for BEVs.

Several tools exist already today, and continue to be developed, to support mining companies in quantifying and visualizing the dynamics of underground BEV hauling, including route planning, speed limits, and location of swapping stations. The importance of batteries in BEV economics equally highlights the need to understand and work with OEMs to optimize the life of batteries through proper maintenance, as well as management of settings for charge and discharge rate, and temperature management.

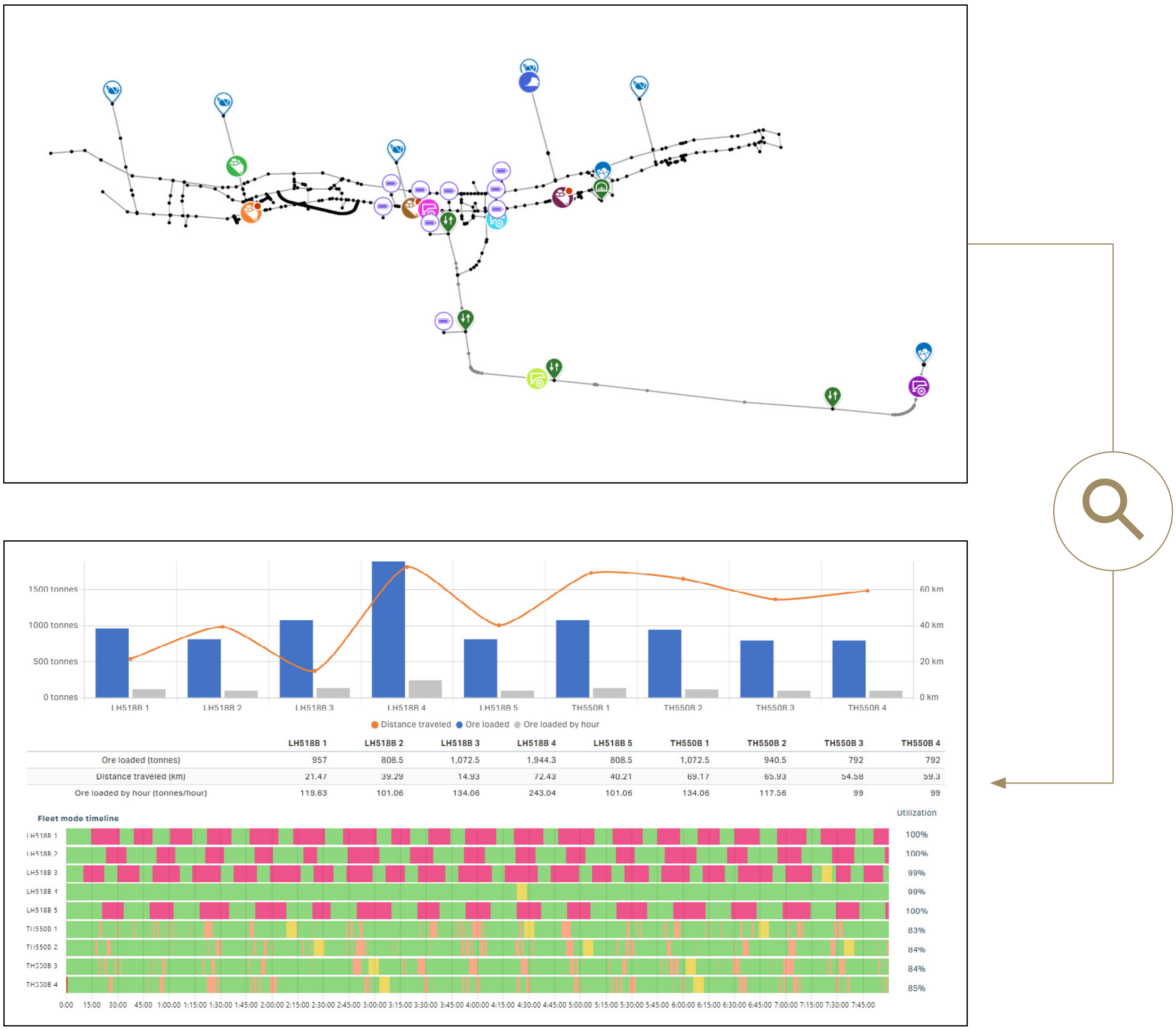
Figure 17: BEV fleet premium vs ICE

% (Fleet unit cost $/tonne), brownfield upramp scenario



As an example, Figure 18 shows an output of Sandvik simulation tool. This model examines haulage profiles (grades/distances) and mine data inputs such as shift duration, production targets, and size of equipment to estimate energy and battery service requirements through physics-based calculations, and also provide optimized (and configurable) battery charging and swapping schedules.

Figure 18: Example of simulation output and energy requirement for a given hauling cycle profile



	LH518B 1	LH518B 2	LH518B 3	LH518B 4	LH518B 5	TH550B 1	TH550B 2	TH550B 3	TH550B 4
Ore loaded (tonnes)	957	808.5	1,072.5	1,944.3	808.5	1,072.5	940.5	792	792
Distance traveled (km)	21.47	39.29	14.93	72.43	40.21	69.17	65.93	54.58	59.3
Ore loaded by hour (tonnes/hour)	119.63	101.06	134.06	243.04	101.06	134.06	117.56	99	99

It should be noted from Figure 16 that the business case for BEVs is not as sensitive to electricity costs as one might expect. This is due to several reasons, including regenerative braking which may lower overall electrical energy requirements, and the reduction in ventilation and cooling energy, which offsets charging power requirements.

Additionally, it is clear that BEVs reduce sensitivity to ventilation capital costs and energy requirements in comparison to a ICE fleet.

Overall, while assumptions and the modeling may differ from site to site, assumptions that are considered and configurable in our techno-economic TCO model are listed in Table 2.

Table 2: Variables in BEV Techno-Economic Modeling

Site level assumptions	
Financials	Cost of capital
	Carbon price
Energy prices	Diesel price
	Electricity price
Emission factors	Diesel emission factor
	Electricity emission factor
Production	
Mine	Production profile and mine life
	Hauling profile (grades, distance, rolling resistance)
	Shifts duration, effective time
Ventilation	Ventilation capital expenditures
	Energy requirements
Cooling	Cooling capital expenditures
	Energy requirements
Infrastructure	
	Capital costs – electrical infrastructure
	Operating costs, maintenance
	Capital costs – swapping bays
Equipment	
Capital costs	Equipment model
	Vehicle capital cost
Operating costs	Driver
	Maintenance
	Tires
	Lubricant
	Battery usage per operating hour
	Energy consumed per vehicle per shift
	Round trip system efficiency
Physicals	Nominal load
	Availability
	Cycle time
	Battery swapping time
	Number of battery swaps per shift
Batteries	
System configuration	Batteries per vehicle
	Charging systems per vehicle
	Cooling cubes per vehicle
	Workshop chargers per vehicle
Capital costs	Battery
	Charging system
	Cooling cube
	Workshop charger
	Swapping bays
Service scheme	Monthly fixed rate
	Monthly use base rate
	Use based variable rate
	Charging system rental
	Workshop charger rental
	Extra battery rental

4.4 Scenario analysis

Overall, mine design and material movement strategy optimization should be conducted to develop an optimal solution, balancing economics, operational performance, health and safety, and risk. The potential for value optimization is further illustrated in this chart presenting various hauling profiles.

Figure 19: Unit production cost in various hauling scenarios
Net present cost, $/tonne

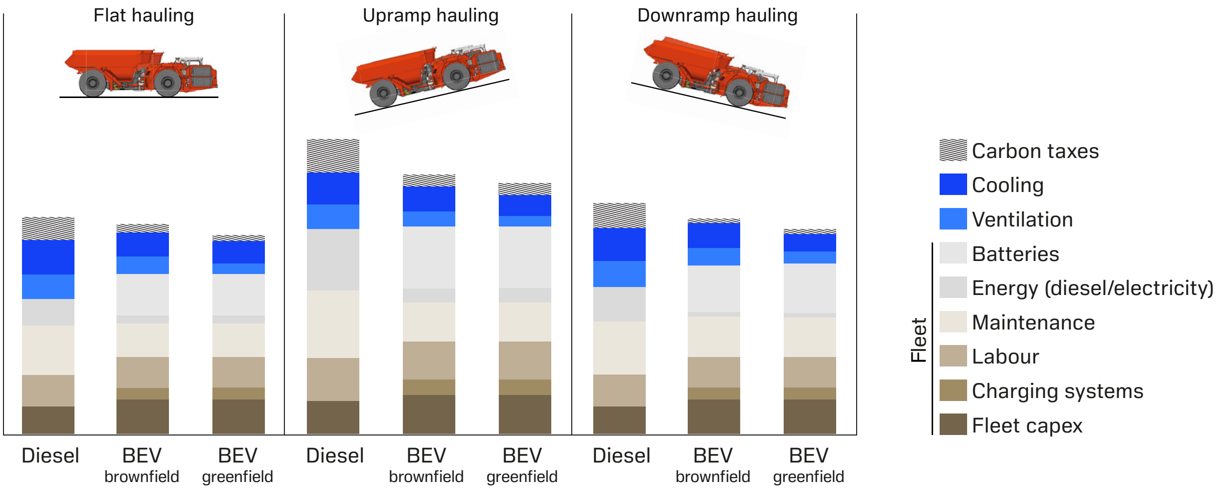
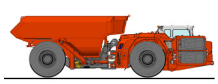
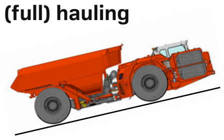
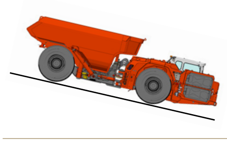


Table 3: Hauling scenarios

While BEV economics ultimately depend on mine level variables, mining method, and ore body geometry, some general observations can be made regarding hauling profiles:

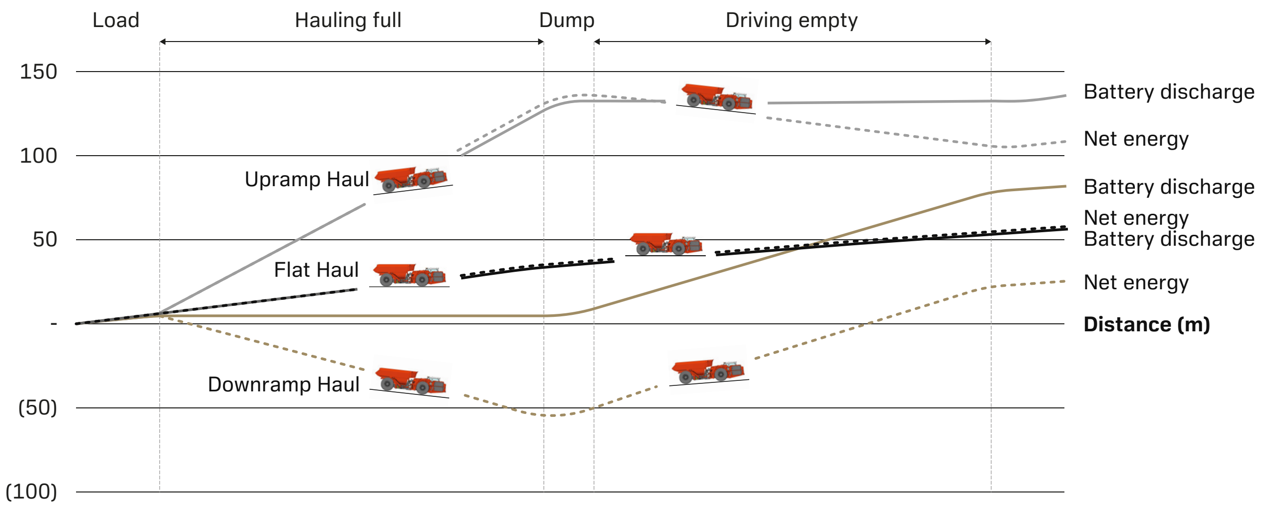
Flat hauling 	— Flat hauling is an attractive use-case for BEVs – no energy is required to overcome gravitation (as opposed to downramp or upramp scenarios). — As a result, this scenario is typically associated with less absolute average power and power variations over a cycle, resulting in less battery wear and longer battery lifetimes.
Upramp (full) hauling 	— This use-case unlocks the productivity benefits of BEVs through shorter cycle time on upramp sections — These benefits can materialize in several ways: i. Lower capital cost: Fewer BEV vehicles may be required than with an ICE fleet, offsetting the higher unit price for BEV vehicles. ii. Lower maintenance and labor costs: shorter cycle times can enable the same level of production with fewer vehicle hours. iii. Additional production: If the operation is truck constrained (because of number of maximum vehicles in cycle, ventilation etc.), benefits may be realized through incremental site production. — Shorter and average length ramps will enable shorter cycle times without the need for extra charging infrastructure. Long and steep ramps may require additional charging stations and batteries. — However, battery power consumption will be higher, potentially leading to unfavorable operating conditions (increased battery temperature and C-Rate), which could lead to more rapid battery degradation. Strong battery management practices for this use-case are essential (and high intensity applications generally, see section on battery management). — This application may have a higher proportion of electricity costs given the more frequent recharging requirements, although this is somewhat offset through regenerative braking when traveling empty downramp. This use-case also implies greater diesel savings given that ICE equipment typically has higher burn rates on upramp hauls.
Downramp (full) hauling 	— This use-case is the least sensitive to electricity costs, given less frequent recharging requirements enabled by increased regenerative braking, as compared to other use-cases. This also results in lower charging infrastructure costs. — Batteries will still experience several charge and discharge cycles given the upramp empty sections (see Figure 20), resulting in higher battery costs than for an equivalent flat haul cycle. — However, significant savings on diesel energy costs are still realized, since energy is still required to overcome gravitation for the empty truck (typically about 40–50% of loaded weight).

It is essential to dissociate the cost of batteries and the cost of energy when conducting these financial assessments. Battery costs are ultimately driven by cumulative usage (i.e., battery cycles).

Figure 20 explains the electrical energy (charging) requirements and battery drawdown or discharge (as a proxy for cumulative usage) for these different use cases.

Under a battery rental scheme, battery costs are determined by energy in and out of the battery when in operation, as both of these actions contribute to battery wear. As a result, regenerative braking doesn't necessarily reduce battery costs/usage, though it does reduce the costs associated with recharging the batteries.

Figure 20: Energy and battery usage requirements per cycle
Measured in kWh (cumulative)
Battery cumulative discharge is represented here as a proxy for battery costs



4.5 Greenfield value optimization

As shown in the previous section, BEVs are currently competitive with ICE equipment in many brownfield operations. In most cases, this will mean managing mixed fleets of ICE equipment and BEVs. A mixed fleet may come with additional management complexity (e.g., procurement and spares management, maintenance, etc.), but form part of a fleet transition strategy to electric.

When integrating a BEV fleet into a greenfield design, additional benefits can be realized, including the avoidance of diesel refuelling infrastructure, and reduced ventilation and cooling capital costs through shaft and system size optimization. Depending on the type of mining method, the ventilation benefits can be significant. For instance, block caving requires flood ventilation and energy requirements can be substantial, highlighting the gains from transitioning to BEVs. In the case where the mining method allows for ventilation on demand (e.g., long-stope mining) and may allow some energy savings with ICE equipment, the gains with BEVs may still be sizeable, as optimization often only targets secondary fan systems without reducing primary fan operation.

Financial forecasting/planning is key in the early stages of project design and production strategy, and it is important to note that BEVs will come with different cashflows than their ICE mechanical counterparts. A BEV fleet will be more expensive upfront, but in some greenfield cases, electric fleets might result in lower overall initial capital costs due to less investment in ventilation and cooling infrastructure and higher operating cashflows if the operator opts for a battery rental scheme.

4.6 Case studies

4.6.1 New Gold – New Afton Mine

In April 2021, New Gold's New Afton mine located in British Columbia, Canada, commissioned its first fully BEV haulage unit – an 18-tonne capacity Sandvik LH518B loader. Since March 2022, the mine also operates Sandvik BEV trucks alongside the LH518B loader. These units make up part of a BEV fleet that seeks to reduce carbon-based fuel consumption at site, one of the initiatives New Gold has implemented to support its 2030 goal of reducing GHG emissions by 30 % across all of its operations.

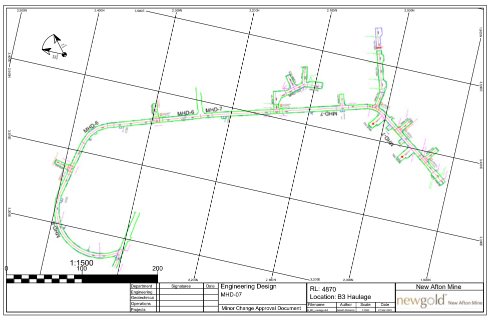
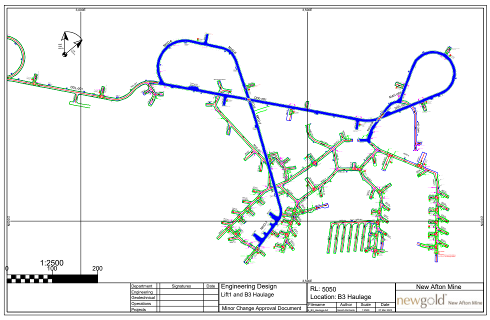
A joint study was performed by CanmetMINING (Natural Resources Canada) and New Gold with the Sandvik LH518B at New Afton in 2022, designed to investigate the additional benefits of transitioning to BEV equipment from production and mine environment perspectives. The study quantified many of the key differences between ICE and BEV technologies. Summarized in Table 4 are the results of a mine production and vehicle performance comparison over two scenarios.

Sandvik LH518B at New Afton.

The comparison demonstrates increased performance from Sandvik LH518B against an ICE comparable – this includes a 60% and 25% average speed increase over scenario 1 and scenario 2 respectively, and 15%–20% production increase.

Aside from productivity-related metrics, the study also quantified differences in air quality and heat generation within the working area. It was found that BEVs contribute to lower levels of respirable dust and heat, in addition to eliminating machine-generated DPM (Diesel Particulate Matter) and CO (Carbon Monoxide) [5].

Table 4

	Scenario 1		Scenario 2	
				
Cycle Distance	870 m		340 m	
Average Grade	13%		2–3%	
	ICE	**BEV**	**ICE**	**BEV**
Duration	4h 56m	4h 49m	3h 46m	3h 50m
Average Speed	7.0km/h	11.4km/h	5.8km/h	7.3km/h
Buckets	37	45	35	40
Energy Use	**Diesel:** 254.5L	**Battery Runtime:** ~2.5hr	**Diesel:** 159.6L	**Battery Runtime:** ~3.5–4hr
Equivalent Energy Use	2,545kWh	692kWh	1,596kWh	383kW

	Respirable Dust*	Diesel Particulate Matter (exhaust)*	CO_2	Average machine surface temperature
ICE	82%	290%	1.3 ton/day	55.9 °C
BEV	18%	0	0.01 ton/day	24.0 °C

*Relative to intake baseline

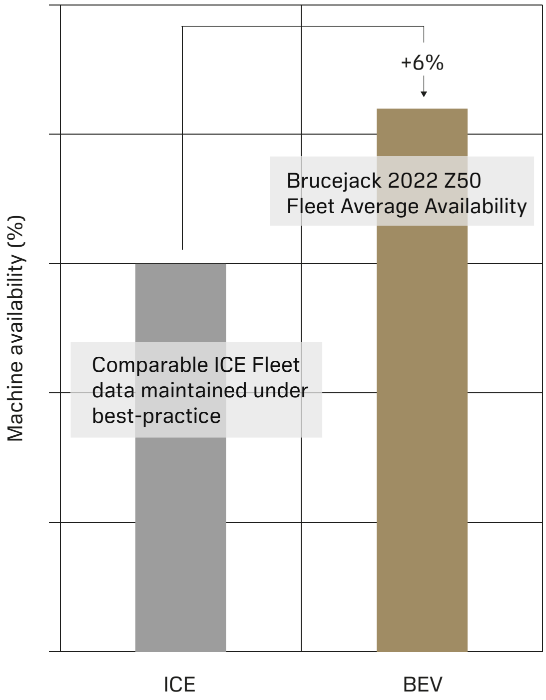
5 E. Acuña, et al. "New Afton Mine Diesel and BEV LHD Field Test: Dust and Heat Contribution Study". Natural Resources Canada, 2022.

4.6.2 Newcrest – Brucejack Mine
Newcrest's Brucejack mine, located in British Columbia, Canada, introduced its first Sandvik Z50 in December 2020. This deployment of the Sandvik BEV unit also accompanies other hybrid haulage unit trials at the site. Newcrest is also planning an electric light vehicle trial at its Cadia mine, as well as an electric road train trial at the Telfer mine, in an effort to deploy electrification-enabling technologies to meet their net-zero emissions goal by 2050.

By Q1 2023, Brucejack had commissioned eight Sandvik BEV trucks and started trials of a Sandvik LH518B battery loader accompanying the truck fleet. Due to high speed and payload capability, Brucejack has benefitted from increased productivity and has achieved a high availability across the BEV fleet, both in absolute terms and relative to diesel equivalents (illustrated in Figure 21). Sites with good maintenance practices may see machine availabilities exceed 90 % when operating a BEV fleet.

A Sandvik 50-ton BEV haul truck operating at Brucejack Mine.

Figure 21: Machine availability – BEV vs ICE



5. Safety

5.1 HSE benefits and risks to be managed

New technology in mining could not be implemented without a rigorous analysis and confirmation that safety is either improved or equivalent to existing technologies. Ensuring a safe operation in underground mining requires stringent attention, as work is generally performed in confined spaces with rigid airflow infrastructure and limited access for hazard response. The underground mining sector prides itself in a safety-oriented culture by imposing high standards to ensure safe operations.

In terms of working environment, BEVs present several benefits:

— Elimination of DPM (diesel particulate matter)
— Less respirable dust circulation
— Reduction in heat generated
— Lower levels of noise
— Lower levels of vibration.

While removing or reducing some risks, BEV equipment and supporting infrastructure also introduce new risks that must be managed: for example, battery fire hazards, presence of high-voltage systems, and new operating procedures such as battery swapping.

The current prevailing philosophy is to mitigate risks by implementing adequate controls and procedures, and ensuring any unmitigated risks are well-understood, with proper contingencies in place in the event of an emergency. Decision makers should understand the nature, likelihood, and severity of these hazards while evaluating BEVs, which are elaborated on in this chapter.

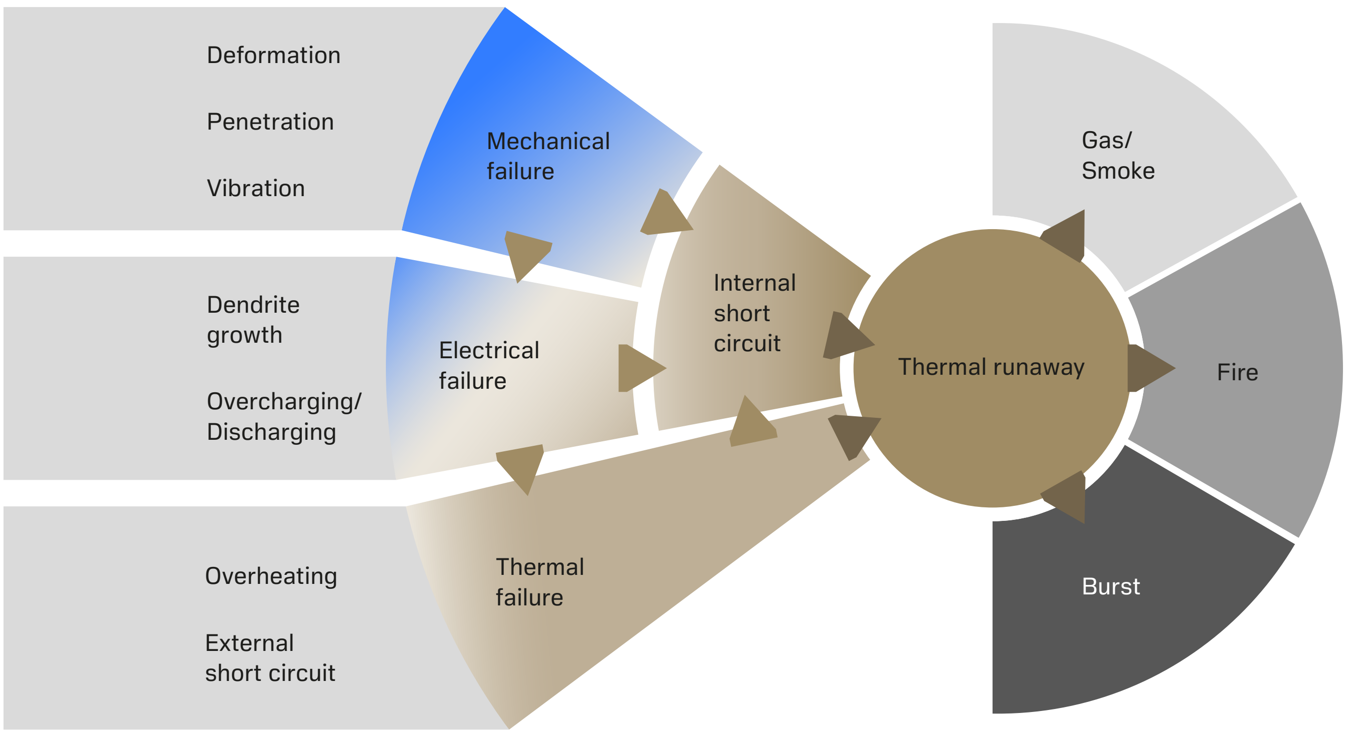
5.2 Battery hazards

5.2.1. Conditions for battery fires

A battery fire can be initiated by various internal and external sources. Internal causes of battery fires are largely related to thermal runaway, whereas an external source pertains to non-battery-initiated fire that migrates into the battery.

Thermal runaway is an electrochemical process which leads to cell venting, fire, or bursting. Once a cell's temperature reaches a critical limit, it initiates an internal short circuit which generates thermal energy and continues to increase in temperature until failure (venting, fire, or bursting). There are several scenarios which may lead to cell thermal runaway, such as mechanical abuse, electrical abuse, or thermal abuse and can help initiate the right responses.

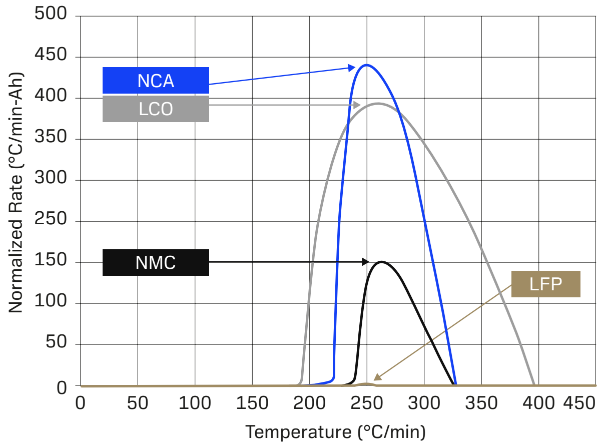
Figure 22: Causes and Outcomes of Battery Thermal Runaway



It should be noted that lithium-ion batteries are available in different sub-chemistries, which are not all equally susceptible to thermal runaway. Different sub-chemistries include LFP (Lithium Iron Phosphate), NMC (Nickel-Manganese-Cobalt), NCA (Nickel-Cobalt-Aluminum Oxide), LCO (Lithium Cobalt Oxide). Heat release rates, ignition temperatures, and gaseous release type varies from chemistry to chemistry.

Sandvik utilizes the Lithium-ion chemistry Lithium Iron Phosphate (LFP) to further reduce the likelihood and severity of thermal runaway incidents. Figure 23 illustrates heat release rates (HRR) of various lithium-ion sub-chemistries. HRR plays a significant role in the initialization and propagation of thermal runaway.

Figure 23: Heat Release Rates for various battery chemistries



Source: “New developments in battery safety for large-scale systems”, Lamb et al. (2021)

5.2.2. Battery Fire Response

In the event of a fire in the battery electrical system or other non-chemical battery components, the in-battery FSS will aid in preventing fire propagation to the cell/module level. Generally, an in-battery FSS will automatically engage at high temperatures, but can also be initiated manually. When engaged, the fire suppression system fills the battery with an electrically non-conductive aerosol agent that chemically inhibits combustion.

If a battery undergoes ignition or is exposed to external thermal hazards that cannot be controlled, hazardous gases might form. It is recommended that operations integrate air quality sensors in regions where BEV equipment is present. These sensors would measure for Hydrogen Fluoride (HF), Carbon Monoxide (CO), and other gaseous emissions (hydrocarbons, nitrous oxides) that may be present during or after a battery fire.

Battery Fire Suppression System example

Heat activated aerosol generators

Electrically non-conductive fire suppression system that fills the pack interior with an aerosol agent that chemically interrupts combustion.

Non-destructive on discharge

Fire suppression agent does not damage the pack interior components.

Quick maintenance

Discharge media stays in the air and can be blown out of the enclosure. Used suppression canisters are simple to replace.

5.3 Other electrical Hazards

The mining industry is already well-established when it comes to safe handling and management of High Voltage (HV) systems – whether it be in general mine electrical distribution or tethered electric vehicles, drills, or similar. When implementing BEVs, it is prudent to review HV safety principles with machine operators, maintenance technicians, and any personnel who may be working on or with BEVs. These principles typically include:

- Cable management
- Reviewing areas where contact risk is present
  - Battery/charger connections, module connections
- Reviewing manufacturer Standard Operating Procedures (SOPs) for charging and other procedures that would require interacting with HV systems
- De-energizing electrical systems
  - Reviewing manufacturer SOPs for de-energizing batteries & chargers, disassembling batteries into lower-voltage state (i.e., module-level)
- Isolation faults and grounding.

6. Fleet deployment

There are several site-readiness tasks an operation must complete to successfully deploy a BEV fleet. Initial phases of a project require the establishment of charge bays and associated infrastructure, while the post-deployment phase requires a readily applicable asset maintenance program and the definition of relevant performance metrics. When considering the vast array of charging philosophies, equipment rental options, and service agreements amongst OEMs, BEV ownership may vary in form. However, planning and development is required, regardless of technology type or ownership model.

6.1 Five success factors for BEV deployment

1. **Plan ahead** – do not wait until equipment deployment to assess technical feasibility and integration plan of BEV equipment. Leverage OEM tools and services to gain a better understanding of charging needs based on proposed cycles, as well as route optimization during the pre-feasibility stage.
2. **Know local regulations** regarding electrical standards before the delivery of BEV products. This allows both the mine and the OEM to ensure all region-specific product standards are met and that all personnel who will be installing HV equipment are qualified to do so by local regulations.
3. **Adopt BEV and battery performance metrics** – ensure systems have been established to track vehicle and battery-related health metrics (as described in Chapter 7) before the commissioning of battery equipment.
4. **Map out battery operating disciplines** – ensure that a battery movement and storage plan is in place before the delivery of BEV products. In some cases, it may be necessary to move batteries and battery-related components throughout the mine for servicing or relocation purposes. Spare batteries should also be stored in a dry, temperature-controlled environment. Extra batteries should also be used and cycled in production in order to avoid storage drive degradation patterns.
5. **Develop your capabilities** – assign an on-site individual as "Project Champion" during early project stages. This role supports and communicates with key departments (Health & Safety, Maintenance, Operations) to ensure all BEV-related integration activity is harmonized at site.

6.2 Readiness plan

In the following section, the BEV deployment process is split into segments relating to project timeline. The details in these segments reflect general themes that require consideration when deploying a BEV fleet. Note that these tasks and recommendations may vary based on the specific details of the project (i.e., mine type, fleet size, charging philosophy, etc.). However, this section can be seen as useful learning and guiding material before deploying BEVs.

Most of these tasks require thorough analysis prior to the submission of an equipment purchase request, while others should be completed immediately afterwards. OEM tools may be available to provide mine design and fleet optimization insights required in this phase of the project. Project definition tasks include:

— Fleet size optimization
  - Vehicles, charge bays, charge bay placement, and design

— Optimize mine layout and design for BEV
  - Greenfield – potential to reconfigure haulage routes to optimize battery performance/usage/regeneration
  - Brownfield – for productivity improvement and cost optimization, as well as for major expansions

— Assess electrical distribution requirements and impact

— Establish OEM and site project team

— Establish project KPIs from OEM and site.

An overall BEV readiness plan should synchronize with the management of existing fleets, for instance, by aligning BEV deployment ahead of planned fleet retirements to ensure continuity of production. Operators may elect to do a full switch to BEV, or a phased roll-out. Trade-offs inherent to managing mixed ICE and electric fleet should be carefully evaluated:

— Additional complexities exist in managing a mixed fleet: differences in equipment performance, such as cycle time, could lead to operational delays. Maintenance of a mixed fleet also requires carrying a larger spare part inventory and corresponding organizational capabilities.

— A mixed fleet could also be a positive initiative, by allowing the organization to build up the skills to manage a BEV fleet. We have found that these pilots and phased rolled-out are most successful when transitioning full sections of the mine or one type of equipment at a time.

6.3 Fleet rollout

Once the project has been defined, the supporting infrastructure will need to be established. This segment outlines the development of charge bays, service bays, and telemetry development. It is recommended that the following infrastructure is completed at least 90 days prior to equipment arrival on-site.

Charge Bays
— Excavation or existing space allocation
— Fire response materials
— Electrical service installation
— Charger/cooling unit placement.

Service Bays
— Adapt existing workshop
  - Electrical service installation
  - Parts storage allocation
  - Workshop charger placement
— Design new workshop
  - Excavation or existing space allocation
  - Parts storage allocation
  - Crane installation
  - Fire response materials
  - Electrical service installation
  - Workshop charger placement.

Telemetry Services
— Wi-fi data connection in charge bays/service bays to transmit battery & vehicle performance data
— Extending wireless connectivity mine-wide will allow for real-time equipment tracking when in operation.

Once the infrastructure has been established and the equipment is on-site, with organizational capabilities developed, the following tasks should be scheduled and completed:

— Parts procurement and storage
— Equipment commissioning
  - Vehicle and battery commissioning
  - Charger/cooler installation
— Deploy fleet dashboard for mine personnel
— Establish performance indicators (KPIs) reporting and tracking tools.

6.4 Skills and capabilities

Mine planning, projects, and operations should closely coordinate as highlighted in earlier sections during design phases, and this should continue during implementation.

The adoption of BEVs necessitates increased fleet management efforts simply due to the addition of batteries and charging systems, whose maintenance schedules and labor allocation should be handled in similar ways as any other capital asset. Depending on the existing service agreement with the OEM, these labor resources could be either in-house or OEM contractors and should preclude the full scale of BEV operation.

In terms of maintenance of BEVs and related equipment, there are several tasks which may be performed by traditional heavy-duty mechanics, such as tire changes, hydraulic work, repair of weldments, and so on. However, haulage BEVs and related equipment (batteries, charging infrastructure) consist of high-voltage systems and components which, when serviced, may require a technician with high-voltage certifications. Moreover, in some instances, it may be necessary to enlist the service of an OEM technician to help diagnose or repair the more complex control/embedded systems issues required to operate a BEV.

From a logistics perspective, sites with large fleets have experienced greater operational success when implementing a labor resource which is dedicated to the coordination and allocation of batteries. This individual is responsible for the communication between vehicle operators, operation, and maintenance departments for all battery asset-related activity. These coordinators aid in the daily reporting of battery and charge bay status, operator comments on battery performance, the allocation of batteries to specific areas/units, and the coordination of battery moves when service is required.

Further considerations
In addition to the above guidance, there may be region-specific certifications and standards that need to be met before implementing BEV technology. In the early stages of the project, the scope of region-specific certification testing and inspections should be defined so that the OEM ensures equipment complies with local regulations.

Example of charge bay configuration.

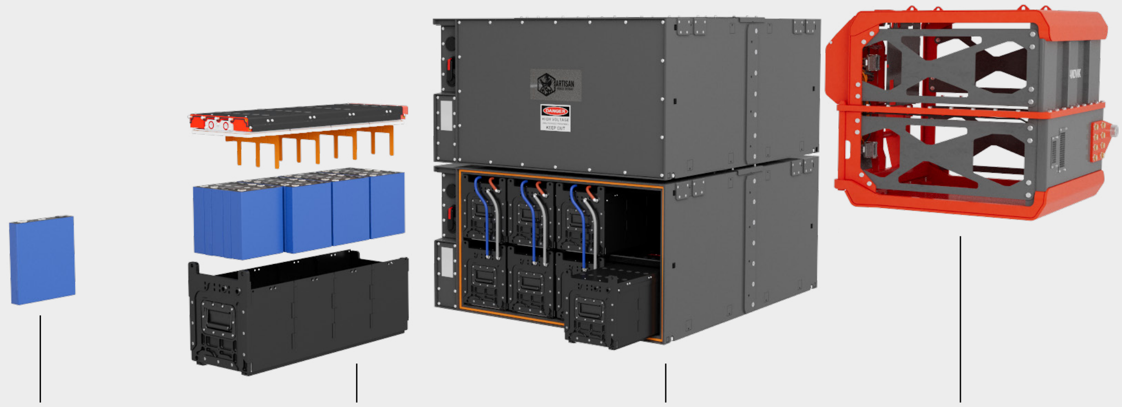
7. Fleet management

Successful management of a BEV fleet requires proactive and compliant maintenance practices. From a vehicle perspective, BEVs generally require fewer maintenance interventions than ICE equipment. However, batteries and supporting infrastructure (chargers, coolers, charging bays, and associated electrical distribution) require specific maintenance and attention to individualized health-related metrics to optimize performance and ensure safe usage. This section focuses on the unique maintenance considerations for BEVs.

7.1 Battery asset management

Unlike traditional fuels, batteries are a form of reusable energy storage and should be treated as an additional asset to the vehicle they are supporting. Battery assemblies are made up of individual cells which are grouped into modules, which form packs and are carried and protected by an outer cage.

Battery System Design



1. Cell
Chemical energy storage element with safe chemistry and built-in protections.

2. Module
Low voltage for safe service. Voltage/temperature monitoring (Battery Management System) and cooling.

3. Pack
Mechanical protection, safety disconnects, isolation monitoring, fire detection, and suppression.

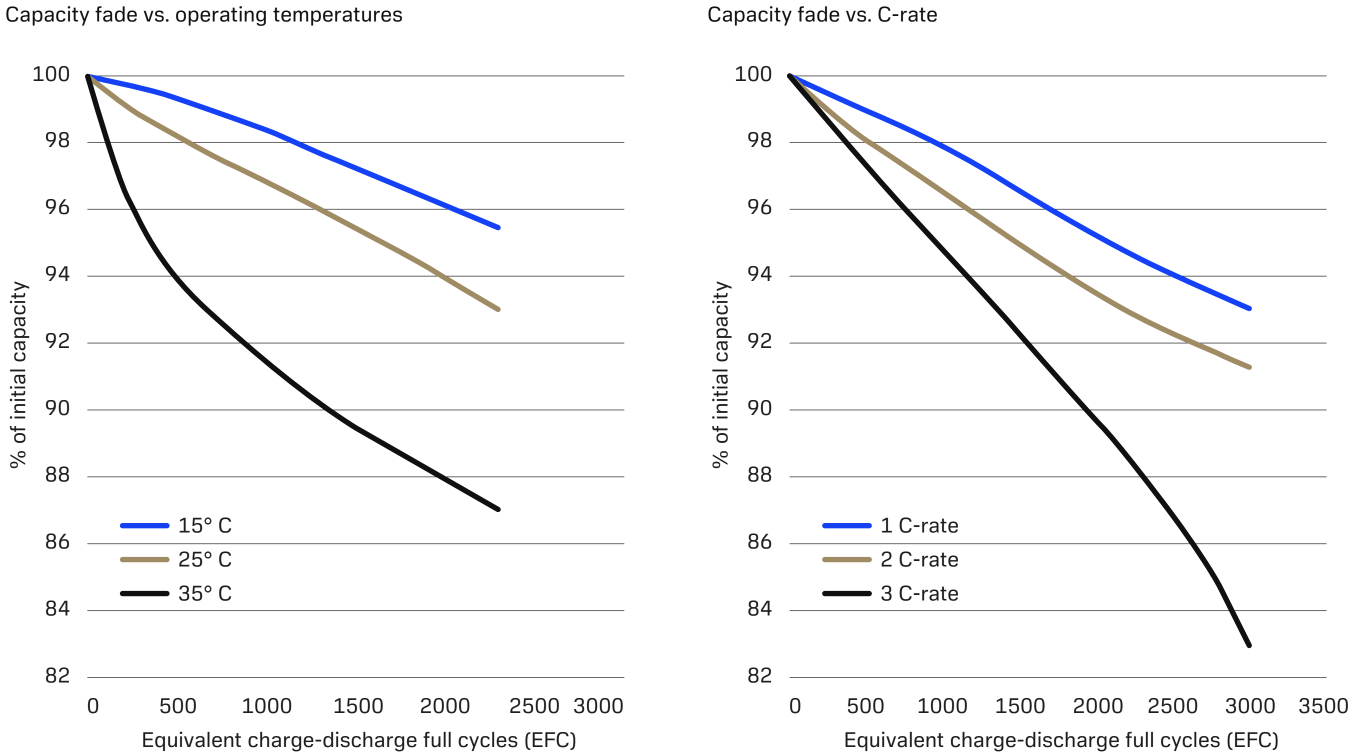
4. Cage
Robust mechanical protection, mobility, and swap-ability.

An important consideration when operating BEVs is that the performance capability of a battery cell decreases throughout its lifetime, and this degradation is sensitive to the level of maintenance dedicated to the battery. Key variables to consider are:

- Battery charge and discharge temperature
- Battery charge and discharge rates
- Battery depth of discharge
- Battery capacity testing & balance cycles
- Adherence to recommended scheduled maintenance interventions.

Cells generate heat during use – particularly in high-current discharge scenarios such as upramp hauling. As shown in Figure 24, operating temperature has a significant impact on cell degradation and useful cycle life. Additionally, high charge/discharge currents and deep-discharge profiles lead to accelerated cell degradation. To mitigate degradation, it is important to consider a battery cooling system (Sandvik has opted with off-board stationary battery cooling while charging, other OEMs employ passive on-board cooling methods), and adhere to an operating schedule that allows for longer, less severe charging cycles. OEMs are continually testing and improving battery performance in various operating conditions.

Figure 24: Indicative effect of battery temperature and C-rate on degradation



Sandvik analysis based on: Y. Preger et al (2020). J. Electrochem. Soc 167 120532.

Given these elements relating to battery management, several practices should be implemented to preserve battery health. One aspect relates to optimizing hauling cycles and battery fleet size to manage depth and number of discharge cycles. Additionally, while parts replacement and associated labor on the batteries is limited, routine conditioning tasks need to be performed to ensure optimal cell State of Charge (SOC) to maximize battery performance. Minor operating temperature discrepancies within a battery may lead to cells discharging unevenly. It is recommended that a battery undergoes a capacity test and balance cycle once every 2–3 months to evaluate and calibrate battery cell SOCs.

Battery capacity testing and tracking is essential for understanding the up-to-date full performance capability of a battery: additionally, it also provides insight into signs of battery end-of-life. A site should determine an appropriate trigger capacity (based on a minimum cycle time a battery must last before needing to recharge) that will initiate the battery decommissioning/refurbishment process, and coordinate with the OEM for the procurement of new batteries. In some cases, the OEM may be responsible for providing end-of-life services as per previously agreed upon capacity guarantees.

7.2 Operating strategies and tactics

With the introduction of BEVs, several associated metrics will provide the necessary guidance needed to achieve optimal mining performance. From an operations perspective, metrics related to machine productivity, performance, operating costs, availability, and utilization continue to be critical, similar to ICE vehicles. In the case of brownfield operations, ICE/diesel comparative data may be useful to further justify the transition and any additional future BEV fleet expansions/conversions.

The utilization of BEVs will depend on the health of the entire battery ecosystem, (ie., availability/health of batteries and charging infrastructure). Given this, additional metrics require close attention:

- Individual battery availability
- Individual battery capacities, operating temperatures, average C-rates, and other metrics affecting capacity
- Individual battery planned maintenance, cycle test and balance intervals
- Individual battery operating costs
- Battery charge bay availability
  - Ensuring cooling infrastructure and chargers are working
  - Battery allocation and space logistics
- Battery charge bay operating costs
- Battery charge bay planned maintenance intervals.

These metrics will provide a clear understanding of the BEV ecosystem availability and function.

7.3 Maintenance and electrical

New maintenance tasks related to the management of BEVs will require coordination with the operations department. Mutual understanding of battery and charge bay scheduled downtime (as well as regular vehicular scheduled downtime) will allow the operations group to accommodate the temporarily unavailable equipment that supports the BEV. Moreover, when a battery needs to be moved to a different area for servicing (for planned/unplanned maintenance), operations must consider logistics around the transport of batteries, otherwise, inadequate scheduling/preparation may interfere with regular movement of materials (explosives, shotcrete, ground support, etc.).

Sandvik's battery production facility in Camarillo, California, USA.

8. Future trends

The benefits and trade-offs of BEVs have been presented in more detail earlier. Operators that have transitioned to BEVs point to several key factors in favor of BEVs. Looking ahead, we can expect that the shift towards BEVs could accelerate for several reasons: continued decarbonization expectations from stakeholders, a reduction in battery costs, and improvements in BEV technology and efficiency.

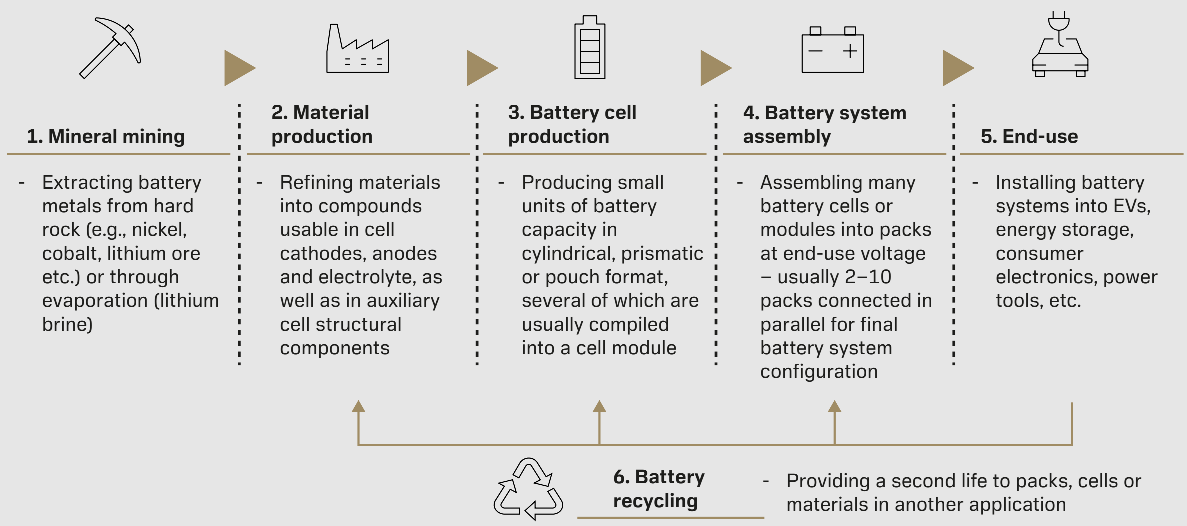
8.1 Stakeholder expectations

Stakeholders within the industry have increased their expectations of mining companies, pushing for a reduction in carbon emissions and demanding an active contribution towards the mitigation of climate change. This has led to most global mining companies committing to aggressive net zero/decarbonization targets over the next few decades. An organization's ability to operate in an ethically, socially, and environmentally conscious manner has also increased in importance, for both mining companies and the governing bodies who regulate them. For these reasons, BEVs have become an attractive and necessary solution to meet stakeholder and regulatory mandates. This is further strengthened by EY's[6] report Top 10 business risks and opportunities for mining and metals in 2023, where ESG was ranked as number #1 for the second year in a row. The next four business risks and opportunities were listed as Geopolitics, Climate Change, License to Operate, and Cost and Productivity – it thus becomes clear that current BEV technology can contribute to solving the top 5 risks and opportunities for 2023. Additionally, operating a BEV fleet will also benefit companies by attracting talent. The best employees will be more likely to want to work with BEV fleets and within an improved work and safety environment.

8.2 Battery economics

Battery performance and costs largely drive the economics of BEVs. As battery technology improvements accelerate, the full life cycle of the battery value chain should be understood, from raw materials supply, manufacturing, and end of life processes.

6 steps of the battery value chain



6 Mitchell, P. (2022). Top 10 business risks and opportunities for mining and metals in 2023. EY. https://www.ey.com/en_gl/mining-metals/risks-opportunities

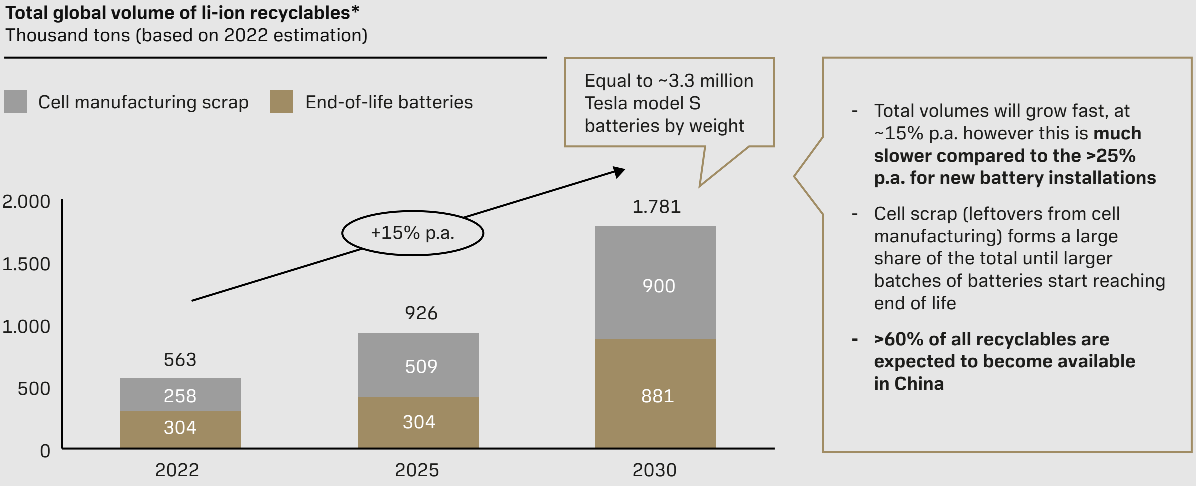
With raw materials supply, geographical and/or political factors may affect the supply of critical resources – the one characteristic that links all the critical metals and minerals together is a perceived risk of demand exceeding supply. According to the IEA [7], to meet the Paris Agreement goals, demand will rise over the next 20 years by more than 40 % for copper and rare earth elements, 60–70 % for nickel, and cobalt, and 90 % for lithium. Mining and minerals companies are responding through large investments in greenfield and brownfield capacity to close this gap by providing this primary supply of metals.

The current trend on the buildup of battery manufacturing capacity is expected to continue, with mass scale production driving down a decrease in production costs as seen for the automotive industry, which are expected to benefit mining operators. However, capacity constraints are already for the EV automotive sector; the demand for such EVs are expected to increase six-fold by 2030. The difference between today's output and promised 2030 output from the world's largest battery producers combined is the balance between 1,360GWh and 5,800GWh[8]. Commissioning a new cell production facility takes years, with its full production capacity taking longer to reach. All in all, such challenges provide reasons to maintain a slightly more conservative view of the positive mass scale effect in price reduction of lithium-ion-batteries in the medium-term future. On the other hand, continued improvement in battery technology and performance are expected to augment the useful life and overall use of new batteries.

Recycled batteries or secondary supply, will come from two main sources: cell manufacturing scrap and end-of-life batteries. In total, these sources are expected to grow to 15 % annually from a baseline of 560 thousand tons in 2022 to 1,780 thousand tons in 2030. Despite a growth in the stock of recyclable batteries, it will likely lag the addition of new battery manufacturing facilities in the medium term. One reason is that the stock of new batteries will have to first reach the end of their useful life before being available for recycling – a duration which is constantly increasing given improvements in technology and performance. Another reason is related to the still emerging technology landscape and the scaling of economics of recycling lithium based batteries.

How much will there be to recycle?

Significant growth expected in recycled material, though at a lower rate than new battery additions



*Recyclable = material available for recycling. Does not necessarily mean material actually ends up recycled.

Source: Circular Energy Storage

7 IEA. (2022). The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions. p.1–283.

8 The Economist. (2022). Could a battery crunch halt the electric-car boom?

With these dynamics, battery recycling is believed to have a modest effect on securing the supply required to meet overall battery demand in the medium term, though certainly, considering the long-term battery materials supply, battery recycling is expected to play a significant role in meeting the growing global battery demand.

Finally, another topic to explore when considering the future of battery economics is the reuse and recycling of batteries being used in BEVs. In many cases, batteries have only degraded a portion of their full capacity before no longer being economically useful in the context of vehicles; however, these cells could be of use in other lower-intensity applications, including onsite applications for use in microgrids as explored in earlier sections. In any case, miners should work with OEMs and regulators to ensure that end-of-life batteries are properly disposed of. The repurposing of used batteries will be a significant element of battery lifecycle management.

8.3 BEV technology

The future of mine electrification will bring many opportunities to the BEV sector as OEMs and mining companies develop their knowledge of the technology through experience and partnerships.

OEMs are working to offer a full suite of BEVs for haul trucks and loaders with similar capacities as ICE equipment as early as 2025, including trucks up to 65-ton capacity and 20+ tonne loaders. An increase in manufacturing scale, continuous improvement in vehicle design, batteries, and charging infrastructure, and connected software systems are expected to drive enhanced BEV performance.

Leading OEMs are investing in BEV manufacturing capacity, which will also enable the optimization, customization, and diversification of the BEV offering. Additionally, OEMs are considering retrofitting traditional ICE equipment manufacturing plants to meet the increasing demand for BEV, ultimately contributing to enhanced value for all mining actors while significantly driving a long-term cost reduction.

To continue this acceleration in BEV adoption, we believe that the mining industry should emphasize the tracking of BEV performance, costs, and safety-related metrics. Industry groups and governmental bodies should actively develop the frameworks to ensure the safe operation and maximization of the benefits associated with BEVs.

9. Conclusion

When considering an underground haulage fleet, Battery Electric Vehicles may already be economically competitive to diesel mechanical ICE vehicles in several scenarios and present additional benefits from sustainability and operator health & safety perspectives. In this document we have compared outputs from our techno-economic model and have presented key drivers for BEV economic feasibility.

In summary, underground operations should consider BEV fleets as part of their material movement strategy. This is especially true when:

— There are clear regulatory or company directives to reduce GHG emissions
— There is a need to procure a new haulage fleet due to aging equipment or the establishment of a new project
— Production can be unlocked in otherwise uneconomic ore bodies due to reduced ventilation/cooling requirements, congestion, etc.
— Applications include flat hauling profiles, or light and medium use on-grade sections
— There are high ventilation/cooling requirements resulting from the use of ICE equipment due to high working face working temperatures and removal of exhaust gases
— Mine electrical infrastructure is sufficiently flexible to support optimal charge bay placement and fleet deployment
— Energy prices are high – both diesel and even electricity in some cases (given that net power load from transitioning to BEVs can be neutral or negative)
— Strong asset management practices are in place.

Perceived operational disadvantages associated with the implementation of BEV such as range/distance limitations, flexibility, and power demand impact can be managed through proper mine planning, design, and execution practices. Several OEM tools already exist to aid in the optimization of fleet size & charge bay locations, as well as simulating production cycles and electrical grid impact.

Other perceived BEV disadvantages such as safety concerns associated with the introduction of a novel technology can equally be mitigated through operator and technician training, equipment monitoring devices and telemetry, as well as the appropriate hazard response materials which may vary between technology type. Operations with a short life of mine, access to low cost of diesel, low ventilation/cooling operating costs, design which consists of long on-grade routes, and weak asset management practices may find it difficult to achieve the full economic benefits of BEVs and manage the additional assets and technology.

For an operation or project wanting to implement a BEV fleet, key first steps include: obtain alignment between site sponsorship and site operations on the potential benefits of BEV; investigate the feasibility of BEVs with the mine planning team, considering variables such as mine design, fleet parameters, ventilation/cooling infrastructure, and electrical infrastructure; and engage OEMs to better understand BEV offering, machine performance capabilities, charging philosophy & available charge bay designs, and leverage available OEM tools to further optimize BEV-related operation.

As understanding of the benefits and the performance of BEV technology in underground operations continues to strengthen, we believe industry adoption of BEVs will accelerate, enabling a once in a lifetime revolution in the world of underground mining.

Do you have further questions or are you considering moving to BEVs for your operation? Reach out to Sandvik and Partners and Performance today.

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