The Sandvik LH514BE is understood to be a combination of tethered cable and battery – battery for tramming and cable operation for mucking

Mine electrification: chapter two

Following success stories at mines such as Macassa and Borden, the industry is preparing to go mainstream with its 'electric mine of the future' message, Dan Gleeson discovers

In the last year, mine electrification has become more than just an industry theme.

At mining events, original equipment manufacturers (OEMs), component builders and service providers have launched new electric solutions; at those same events, executives have stood up and waxed lyrical about decarbonising their existing operations; and several mine developers have started to include the use of battery-electric, cable-electric, trolley assist or other hybrid electric machines in the 'potential economic improvements' sections of major economic studies.

As electric milestones continue to be achieved on a daily basis, the industry story is moving from a 'Borden-focused' tale (*see The Borden benchmark*) to one that has many plot points and protagonists.

Collaborating on innovation

Heather Ednie, Managing Director of the Global Mining Guidelines Group (GMG), has been there from the start of this latest electrification movement.

GMG, a network of representatives from mining companies, OEMs, technology manufacturers, research organisations, consultants and regulators around the world who collaborate to tackle challenges preventing the mining industry from progressing, launched its first battery-electric vehicle (BEV) guideline for underground mining back in June 2016 (published 2017). It has since seen the industry mature to a point where miners all over the globe are pushing technology providers to design electric solutions that will allow them to achieve their production and environmental goals.

She reflected on the start of guideline discussions several years ago: "In the early days when we launched the first version of the BEV guideline, safety was always a big concern, but the feasibility to mine was the biggest driver that really accelerated things."

Miners in Canada, such as Glencore and Vale, were simply unable to make a strong enough economic case to build new mines or develop deeper underground levels with the current crop of diesel-powered equipment due to ventilation and air cooling requirements at such depths, she explained.

"It really was: 'we cannot mine if we don't have this technology'," she said.

In Europe, miners like LKAB have also stated they need to consider a different operating paradigm if they are to extend deposits at depth.

This meant that, in the initial stages of developing the BEV guideline, influential participation came mainly from North America and Europe.

"We did have workshops globally, but it was more exploratory – other regions weren't really focusing on it yet," Ednie said. Outside of these two continents, concerns over electricity prices in some regions and a lack of appreciation for the capital and operating costs benefits of employing these electric solutions held others back.

The situation has changed.

"Now, when we get together, diesel particulate matter (DPM), greenhouse gas emissions and other critical topics have become important drivers, much more than they were during earlier conversations," Ednie said. "The interest is now global."

Evidence of that comes from the fact that GMG, late in 2019, launched The Electric Mine Working Group.

Leveraging existing work from the underground BEV guidelines (there have been two published versions with preparations in motion for a third), the new group aims to accelerate the advancement and adoption of electric mining technologies in underground and surface contexts, covering electric technologies replacing those that typically use diesel.

Key objectives for this group include developing guidelines and sharing information on using and testing electric technologies and designing electric mines. This could lead to the development of industry whitepapers, short courses around mine electrification specifics and benchmarking of existing diesel and BEV equipment, Ednie said. Mine site visits are also likely to take place at operations where electrified equipment is already employed.

Even though the members are still in the process of ascertaining which technologies might play a leading role in this working group, Ednie says all participants were quick to rule out any technologies related to using diesel – regardless of how 'clean' this diesel might end up being with DPM removal systems.

GMG's The Electric Mine Working Group is not the only industry collaboration looking at new technologies to decarbonise mining below and above ground.

The International Council on Mining and Metals' (ICMM) Innovation for Cleaner, Safer Vehicles (ICSV) program has seen 27 of the world's leading mining companies and 16 of the best-known truck and mining equipment suppliers corralled into what the ICMM refers to as a "non-competitive space".

The ICSV program was created to address three of the most critical safety, health and environment performance issues in the ICMM's mission towards zero harm and decarbonisation, with the goals closely tied to introducing and adopting the next generation of equipment.

Two of the three specific aims are relevant to this discussion – namely:

- Introduce greenhouse gas emission-free surface mining vehicles by 2040; and
- Minimise the operational impact of diesel exhaust by 2025.

The ICSV program offers a "safe space for the OEMs and members to work openly in a non-competitive environment", Sarah Bell, Director, Health, Safety and Product Stewardship for the ICMM, told ***IM*** in December. The aim is not to come up with "preferred technologies" but define the "functional and operational pathways required to meet the ambitions set", she explained.

As the ICSV timelines indicate, the technology to decarbonise above and below ground is at various stages of maturity.

Bell explained: "The DPM working group have recognised that, in the case of the DPM ambition, 'the future is already here, it's just unevenly distributed'."

While battery power is widely anticipated to be a facilitator of DPM reductions underground, there is less certainty about it being replicated in the open-pit mining space.

"There is a lot of work to do to develop batteries at scale for surface fleet that suit the different operating conditions," Bell said.

eMining's 63 t payload battery-powered eDumper might be suitable for a limestone quarry in Switzerland where it travels unladen uphill and full on the downward return journey, but there are few large-scale mines that fit this profile.

"That's a key point because that lends itself to the fact that we don't want one solution; we will need multiple solutions," Bell said. "We don't want to stifle innovation; we want to encourage it."

It is no wonder then that GMG's The Electric Mine Working Group is working in parallel with the ICMM's ICSV initiative to ensure both support each other and are complementary.

Critically – and perhaps more so than other technology developments of the past – there appears to be strong collaboration on this electrification project between not only OEMs and mining companies, but OEMs and other OEMs.

GMG's Ednie explained: "One of the things that you take away from speaking to some of the companies that have been greatly involved with the BEV guidelines on the OEM side is that being able to sit down with your peers at other OEMs is not something they normally get to do when in the design phase of some new technology."

Considering the cost of developing these new machines and the flexibility that will be required from a charging, infrastructure and design perspective, such collaboration will be integral to all miners achieving their green-powered goals.

No 'one-size-fits-all'

One of the OEMs to have featured prominently throughout the industry's most recent electrification pursuit is Sudbury-based **MacLean Engineering**.

Back at *MINExpo 2016*, the company laid out plans to electrify units across its three product lines – ground support, ore flow/secondary reduction and utility vehicles.

Having completed this goal, with more than 30 production support BEVs now working underground in Canada – at 10 mine sites across four provinces with four major mining companies – MacLean is ready to keep evolving in terms of its product line and electrification message.

Stuart Lister, Vice President of Marketing & Communications for MacLean, told ***IM***: "When you deal with the next generation of wider electrification, which will require different infrastructure and applications, it's not a one-size-fits-all approach."

MacLean's electrification blueprint, to date, has involved adding battery-electric drivetrains and on-board chargers to its BEVs.

Patrick Marshall, Vice President, Product Management at MacLean, explained: "They (the BEVs) critically drive to the face, or mine headings (on battery power), and go into a stationary state to perform a function like running shotcrete, loading ANFO or emulsion, installing ground support, etc.

"The duty cycle of that works extremely well with on-board charging," he said, with miners able to connect the machines to the existing mine power infrastructure to charge the battery when performing these stationary tasks.

"We made the right strategic decision with the operating and charging for these duty cycles – it is cost effective as you don't have to carry spare batteries, you don't have to install extra infrastructure and, where there is power, you have the ability to recharge it," Marshall said.

The company's next line of BEVs will likely require a different tactic.

"Where we are approaching it with new strategies and thinking are applications that require a very long range and payload – transporting of shotcrete material in an agitator truck can, in some mining applications, for example, require very long-range haulage," Marshall said. "Because the machine is only parked up during its unloading cycle it doesn't necessarily warrant an on-board charging strategy.

That is where we start to look at fast charging as the correct strategy for those vehicles."

MacLean's Lister is aware the company's marketing message may also have to be adapted as the company looks beyond Canada for its next crop of BEV sales.

"We're looking to market outside of Canada – where taking a known carcinogen away is the key driver despite the initial upfront capital cost," he said. "In markets that are more price sensitive, how do you make that switch?"

Being able to provide data on more than 40,000 operating hours of BEV equipment will help.

This enables the company to provide an indicative total cost of operations calculation that miners can factor in alongside the upfront capex of the machine in question.

Some of this data is already starting to be shared with companies working on economic studies for new underground mines or expansions of existing operations, the company said, with Anthony Griffiths, Product Manager – Fleet Electrification for MacLean, saying, in December, he was asked for BEV data for three economic studies.

He explained: "That is the first time since I have been in this role that the indication was diesel is not accepted."

Another company keen to engage miners with its BEV databank is **Epiroc**.

The Sweden-based OEM commenced work on a battery-electric Scooptram ST7 back in 2013 and, since then, has accumulated more than 100,000 hours of operation under its zero-emission program.

Franck Boudreault, Global Product Manager – Electrification at Epiroc, told ***IM*** that the company has experienced a range of motivations and required benefits for buying and using its BEVs depending on the size of company, type of operation, and location of customer.

"Whereas one customer or region may focus on DPM reductions or health, another may find the added productivity at high altitude more attractive, or a third one may see heat reduction benefits," he said.

"The beauty with BEVs is that we can achieve all these benefits within the same offering."

This point was also picked up by Mats Eriksson, President of **Sandvik Mining and Rock Technology**'s Load and Haul division.

"The requirements to tailor marketing are lower with BEVs as the technology already brings added value that is of common importance in most market areas," he told ***IM***.

Boudreault said the initial upfront capital expense issue that is so often discussed with these new vehicles has been somewhat alleviated with the company's Batteries as Service offering. This sees miners purchase the battery operation service for the BEVs, as opposed to buying or leasing the batteries.

"The initial cost of an electric vehicle, excluding the batteries, is around 20% more than its diesel counterpart," Boudreault says. "With the batteries included in the upfront cost, the price tag quickly jumps to two to two-and-a-half times the price of a comparable diesel machine, which very few customers are willing to pay."

This shifts the battery cost to an operating expense, as opposed to a predominantly capital expense, plus alleviates any potential issues that may arise with the batteries as Epiroc also takes on the task of maintenance.

Boudreault added: "This does not only make sense from a cost distribution standpoint; it also makes sense when it comes to having the right battery for the right application."

Eriksson said Sandvik was open to a similar solution in the future where customers pay for the kilowatt hours they use instead of buying the battery pack outright.

Such services are likely to gain in importance as battery technology continues to evolve and larger, more powerful units are developed that can increase the range and productivity benefits associated with using battery-powered machines.

Narrowing the gap

While vehicle range is still a factor holding back customers in every market for battery-electric vehicles, the performance advantages are starting to be acknowledged more broadly.

Boudreault says Epiroc's BEVs have outperformed diesel-powered machines during benchmarking trials, with a mine truck on a ramp haulage application yielding 10-12% higher productivity than its diesel counterpart.

And, of course, this comes on top of numerous environmental benefits for both operators and the companies employing the vehicles.

Sandvik-owned **Artisan Vehicle Systems** has also been quick in comparing battery-powered machines with the equivalent diesel-powered variety.

In releasing its Z50 underground haul truck – the largest battery-electric underground haul truck recently on the market – Artisan said the 50 t capacity truck generates twice the peak horsepower and one eighth the heat of its diesel equivalent.

One of these vehicles, powered by four electric motors generating 560 kW and 8,200 Nm of torque, is set to go underground at a US mine, so those claims will soon be tested.

IM understands larger payload battery-electric trucks for the Australian market are also in development by one of the major OEMs, which will allow further diesel/battery benchmarking.

If developments in the battery and component supply chain continue at the same pace as the vehicles itself, the gap between diesel- and battery-powered machines could narrow further.

MacLean's Griffiths explained: "The supply chain is catching up and starting to look ahead and develop things that will extend the battery chemistry, range and charging time."

Acknowledging this evolution, Epiroc's Boudreault said: "The performance gap between electrical and diesel machines will only continue to grow. With improved cell capacity, we will also extend the drive time."

These changes could also see the price gap between diesel and battery-powered machines close, according to **Normet**'s Product Line Director, New Technologies, Jukka Ristimäki.

"When these parts go into mass production – you can see the battery volumes going up – you will see the prices go down," he said.

All about the charge

Normet, like MacLean, started its fleet electrification plans with machines that could tram on battery power and charge while carrying out their stated tasks.

The Finland-based company launched its fully-electric offering for mining and tunnelling construction at the *Bauma* fair in Munich, last year, calling its SmartDrive technology a "sophisticated and fully-engineered battery-electric architecture able to operate underground totally emission-free, saving costs at the same time".

Ristimäki told ***IM*** that the company began its electrification project back in 2015, with its first prototype developed in 2017. It worked with the First Quantum-owned Pyhäsalmi mine, in Finland, to refine its approach before the Bauma launch and, in mid-2019, demonstrated the first battery-electric emulsion charging in a production environment underground with its Charmec MC 605 VE SD at Pyhäsalmi.

Ristimäki explained the company's approach to electrification: "Our concept for the battery utility vehicles is not battery swapping, but fast charging. Battery swapping might be needed for loaders or dumpers, but opportunity charging fits well into the range of vehicles we manufacture."

The company, which focuses on concrete spraying and transport, explosives charging, scaling, rock and ground support, sought to utilise existing power infrastructure underground at mines with these vehicles, but at the same time ensure all of its equipment is compatible with standardised fast charging interfaces like the CCS (combined charging system) protocol.

"In our approach, we also thought it made sense to use that infrastructure and be able to charge with an on-board charger, as well as fast charging, to give the flexibility to the customer," he said, adding that the company supplies battery

chargers from 40 kW all the way to 300 kW.

"From a productivity perspective, with concrete spraying and explosives charging, while you are carrying out the process, you can connect to the power source for 'opportunity charging', rather than use the battery, having no negative effect on the production cycle," he said.

It is the company's medium-size range that has been released to the market as part of Normet's strategy to electrify its existing line of diesel-powered equipment, and Ristimäki said Normet BEVs will start in "real operation" in the June quarter with a multi-purpose cassette type vehicle going to a mine site in Canada and an emulsion explosives carrier application going to Australia.

An electric concrete transmixer unit is also being lined up for trials with another mining customer in a third country, he confirmed.

On the latter, he said: "For me, this is the most interesting case study as you typically bring concrete downhill, so you can really optimise the battery drive there," he said. "According to our simulations, the payback on that application could be very tempting."

Feasible options

As the GMG Electric Mine Working Group and the ICSV initiative hinted at, battery-electric solutions are not the only diesel-power alternatives being factored into economic studies.

Electric solutions that have been present underground for decades have recently been getting a revamp and could find a home in situations where a diesel-alternative is sought but there may still be question marks over a battery-powered vehicle's range.

Boudreault sees trolley-electric solutions being factored into future mine designs.

"For trucks constantly hauling on ramps, a trolley solution is often more economical due to the large energy consumption," he said.

This is why the company is currently looking into the potential benefits of designing a trolley version of its MT42 Minetruck and why its existing Kiruna brand of trolley trucks are still being used at some of Vale's Sudbury operations.

Tethered vehicles may be another alternative.

Sandvik has recently delivered its 600th cable-electric LHD to the LKAB-owned Kiruna iron ore mine, in Sweden, with the LH625iE unit based on the well-proven design of the tethered LH625E that has already been used at the mine for many years.

Eriksson, who was present at the handover of the machine, sees room for both battery and tethered equipment in the industry – in some cases a combination of both technologies in the same environment.

"It's very much dependent on the mine design and what makes most sense," he said.

Perhaps there is room for a battery-tethered hybrid?

While Sandvik Mining and Rock Technology President, Henrik Ager, told ***IM*** that the company was weighing up development of a diesel-battery hybrid (see High Profile, pages 48-49), further along the development pathway is a battery-assisted version of its tethered machine, the LH514E.

Known as the LH514BE, this machine is understood to be a combination of tethered cable and battery – battery for tramming and cable operation for mucking.

The development of a horizontal cable reeling for this machine means there is the possibility to operate with the connecting point on either side of the unit, according to Sandvik, offering increased flexibility over traditional cable-electric designs.

Sandvik is not the only company working on such a machine.

GHH, no stranger to the design, development and operations of tethered electric LHDs having introduced its first such machine in 1978, says it has been developing a new battery-electric tethered loader with a key customer.

The new loader, the LF-19EB, is predominantly for soft-rock applications, and specifically designed for loading into a feeder breaker with a robust T-Kinematic and low total height above the motor compartment, the company says.

GHH explained the design rationale: "Currently some of the soft rock, room and pillar operations are using tethered electric loaders which have the

GHH's new tethered battery-electric loader, the LF-19EB, is predominantly for soft-rock applications and specifically designed for loading into a feeder breaker

benefit of zero emissions and can operate in sections with limited to no ventilation, but unfortunately there is a significant loss in productivity, having to tow the machine with diesel-driven tow trucks between production ends, or get a generator set up to be able to drive it to the other stope."

This effectively means that although the vehicle may have high availability and productivity while working, it suffers overall low utilisation.

The new GHH machine is equipped with a battery for tramming up to 2.5 km (depending on the ground condition), without the use of any utilities such as generators, and with greater independency than traditional tethered electric loaders, the company said. "This effectively improves the utilisation of the vehicle per shift, therefore improving productivity considerably."

The machine comes with a 19 t payload capacity, a tractive effort force of 380 kN, an average of 250 kVA under permanent load and 315 kVA peak, and has a maximum cable length of 250 m.

The loader can cope with the very high temperatures and undulating footwall conditions often found in underground soft-rock salt mines, according to GHH; it is able to operate at a maximum of 28% grade, 15% slope and at 52°C. On top of this, the rear of the machine is ergonomically designed with low and flat top covers to allow for maximum visibility for the operator as well as good manoeuvrability in tight spaces.

The new battery-electric tethered loader comes with a significantly lower operating cost than both a diesel LHD and a traditional tethered electric LHD, GHH said.

"Not only does the regenerative braking reduce both brake and tyre wear, thus reducing the predictive operating costs, but there is also no diesel engine, therefore no refuelling and a lot less maintenance due to having electrical components," the company said. "The LF-19EB requires far less ventilation and also generates far less heat compared with a diesel LHD, resulting in a less negative impact on the operator."

Thanks to a direct driven gear box, axles and an intelligent motor management, the ride is extremely smooth, according to GHH, something that will be welcomed by any operator.

"This loader is a perfect intermediate between tethered electric and a pure battery solution," the company continued. "It is more flexible than a tethered loader and less risky than a pure battery loader, as long as the battery technology does not meet the requirements of an eight-hour shift. It is the perfect solution, especially for existing mines, when it comes to the power supply system because the battery is not only designed for moving the loader without cable, but also to buffer peaks in power consumption and recuperation."

To charge, or change out?

Just as MacLean's Marshall indicated, the need to charge battery-electric machines varies depending on the application.

Companies such as Artisan are sticking to a battery change-out policy to improve the productivity of its battery-powered loaders and trucks – a solution set to become even more efficient with an automated change-out process in development – while others use either an on-board or off-board charging solution.

Adria Power Systems, which has been building electrical infrastructure for mining for almost 25 years, specialises in the latter. Over this period, the Quebec-based company has built up a reputation for rugged and robust electrical chargers suited to underground mine conditions.

IM caught up with Mathieu Bouffard, Adria Project Manager, to discuss the latest developments in the company's offering.

The company has recently been working with **Miller Technology** on a CCS charging protocol for Miller's Relay electric utility vehicle at the Alamos Gold-owned Young-Davidson mine, in Ontario.

The new generation charger from Adria allows for Level 3 DC fast charging via this protocol with type 2 plug as recommended by the GMG BEV guideline.

Bouffard explained: "We've built another charging prototype before, but this is the first one with a CCS protocol.

"We have just finished building the second one (CCS-type charger), which is going to be more powerful using two DC/AC outputs, which will be working in interleave mode. That upgrade is so we can filter and regulate the charge at any voltage/current with the same efficiency."

The company's goal is to, within a month or so, swap the charger currently underground at Young-Davidson with this upgraded charger, then take the older charger to Kirkland Lake Gold's Macassa gold mine, also in Ontario, to integrate into the CAN bus-type battery-electric machines working there.

While Bouffard was not certain all BEV manufacturers would move to the CCS protocol that the likes of Epiroc and Normet are pushing for, he did say there were plenty of benefits to the design.

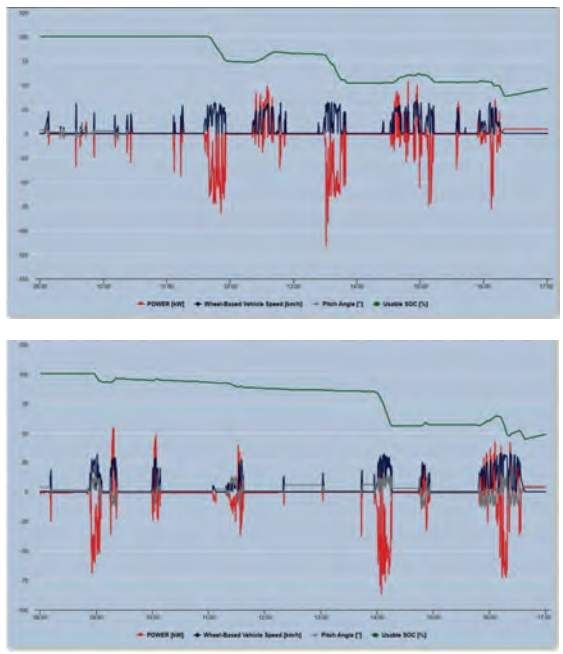
"Working with the CCS, we have realised it is so well made – it's so complicated that it cannot be hacked and there is a start-up routine that does all of the safety checks with the cables, so it is really robust and safe. There is no room for human mistakes within this."

In addition to working on a "bi-directional version" of this new charger – which could be available later this year – Adria's Bouffard said the company was also developing a high-powered 4 MW charger for surface vehicles. This work is being conducted over a three-year period so may find its way into the development plans for the new crop of all-electric open-pit mines like Nouveau Monde Graphite's Matawinie project, in Quebec.

Judging by the data coming through from the Miller Relay electric utility vehicle, the unit has been working well at Young-Davidson.

Paul Summers, Lead Developer, Electric Drive Systems, at Miller, said that, for utility and support applications at least, Miller is finding battery-powered electric vehicles are completely viable even in hard-rock mines with steep ramps (see graphs).

Randy McCooeye, Safety and Risk Assessment



During two days of utilisation from a beat mechanic (one of the higher daily mileage duty cycles for light vehicles) at Young-Davidson, Miller Technology's Relay electric vehicle was able to complete work without opportunity charging and, at the end of the shift, there was still more than 30% charge remaining, Paul Summers says

The Borden benchmark

The 'all-electric' Borden mine in Ontario, Canada, has been spoken about for years in mining technology circles.

Having now achieved commercial production safely, on schedule and within budget, *IM* felt it was the right time to reflect on the project's achievements. Maarten van Koppen, Manager, Energy & Sustainability at Newmont, was more than happy to provide some answers to our questions.

IM: Goldcorp (prior to the Newmont acquisition) guided for significant ventilation cost reductions with the use of battery and tethered electric equipment at Borden. Have these projections been accurate in terms of the amount of air the ventilation on demand (VoD) system has had to push to the mine?

MvK: In the study phase of the project an electricity budget was prepared for the life of mine and it was based on first principles. Unfortunately, there were not a lot of benchmarks available for an all-electric ramp haulage mine, which is one of the downsides of being one of the first movers.

As it turns out, the predictions were too conservative as the actual electricity consumption was significantly lower than our expectations by about 40%. The savings are attributable to continuous improvement in the ventilation engineering, a more efficient VoD system than anticipated and lower energy requirements for equipment than originally anticipated.

What's interesting is that the instantaneous peak demand is close to what we anticipated, and we are working with the utility companies to expand the grid capacity at Borden to ensure we can continue to grow Borden as planned.

IM: Have there been any unexpected benefits of implementing the battery and tethered electric equipment on mine operations/productivity/maintenance/worker interaction, etc?

MvK: We expected buy-in from the operators, though the feedback was much more positive than anticipated. At the end of the day, people feel better leaving work because it's a healthier work environment. This is the most important benefit of all. It probably helps attract and retain people at Borden as well.

IM: Conversely, has the tethered/battery-electric equipment caused any issues in terms of flexibility/charging requirements at Borden? How have you overcome these? Do you expect to add/change the electric fleet at the mine as production continues?

MvK: Of course, there have been setbacks, it would be naïve to think that the introduction of a lot of new technology would go without a couple of snags along the way. The way to overcome this is to partner with the OEMs and contractors, foster a 'can-do' attitude on site and persevere. The team at Borden has done some amazing work over the last couple of years. Some of the adversity was in the chargers, which had to be replaced and tweaked before we got them to work. Harmonics on the mine grid from variable frequency drives for fans and pumps caused some of these on-board chargers to malfunction. Similarly, a custom-converted road grader has been causing a lot of issues in the controls and has caused a lot of headaches.

The charging requirements are actually quite simple for the most part at Borden. The vast majority of equipment has on-board chargers that can be hooked up using the common jumbo plug. This greatly reduces complexity. There are some exceptions, for the personnel carriers for example, and those are manageable.

There are still some machines that we are looking to replace with an electric counterpart; we expect the production drill later this year and we still operate diesel haul trucks.

IM: Outside of Borden, where else in the portfolio does Newmont have tethered or battery-electric equipment? What, if any, changes to mine design are required for this implementation?

MvK: We operate battery-electric equipment at Musselwhite and Eleonore. Virtually all new underground mines stand to benefit from going electric.

For existing mines, the business case of switching is much more of a challenge to compile. One of the prerequisites to extract full value out of going electric is a sophisticated VoD system and the ability to modulate air flows, which requires connectivity underground and a way to track equipment and personnel in real time. Quite often those upgrades are not straightforward for mines that have been around for years. In addition, the ventilation infrastructure is already in place so capital savings cannot be realised unless upgrades are required to grow or continue the operation.

IM: Knowing what you now know after embarking on such an ambitious project, would you have done anything differently?

MvK: What we know now, a couple of years down the line, is this whole field moves rather quickly. There are very few regrets with Borden, and certainly none of them are big ticket items.

Electrification it is now a lot easier than when we started because the product offerings by the OEMs are a lot more extensive and there is a growing level of experience in the industry when it comes to electric equipment. The real question is what is the next frontier in the next mine of the future, and I think the answer is fully autonomous and carbon-neutral operations with perpetual performance improvements through gamification and AI, while meeting societal expectations regarding sustainability and wealth creation in the communities where we operate.

Coordinator for Alamos Gold's Young-Davidson mine, said he had been testing the Relay for around eight weeks – in rough environments and going up and down ramps and inclines on numerous levels of the mine.

"Compared with diesel, I'm lost for words. Health-wise, in terms of the effect on employees underground, it's amazing!" he told *IM*. "I have driven this unit all shift so far without charging it until shift end as it charges itself on a decline. I started it at 97% charge and, at the end of the shift, it was 33% – that's amazing for travelling throughout the 5,000 ft (1,524 m) deep mine."

He said the machine takes 15 minutes on the fast-charge 650 V setting to get to near-full capacity, while there is a 240 V charging option that takes six to eight hours to hit the 100% mark.

Aramine has decided to hedge its bets and devise both an on-board charging system as well as a battery change-out option for its miniLoader® L140B.

The 1.3 t capacity narrow vein loader has been in operation since 2017 in several mines around the world, with the on-board charger providing around four hours of continuous operation. This allows for the mucking of three to four faces in one shift, according to the company.

The quick replacement system (QRS), however, features a quick disconnect battery module that boosts productivity further. "It allows running the machine full time without immobilisation during charging time," the company said, adding that the QRS process takes about 10 to 15 minutes to carry out.

In order to safely manipulate the battery module, Aramine's R&D department is currently developing a Mobile Charging Station (MCS), the company said.

"Compact and practical, it is equipped with a hydraulic crane for quick and easy changing and moving of the battery modules. The station is connected to the mine's electrical network and is piloted easily be a radio remote control," Aramine said.

The launch of the MCS is scheduled for the middle of the year.

Caterpillar, too, has come up with a mobile charging solution. It's MEC500 offers ultra-fast battery charging with the 300-1,000 V output capable of providing up to 500 kW of power. Such a solution will come of use when the company

The 15 t R1700XE will be Cat's first battery-powered underground loader

launches its eagerly awaited R1700XE 15 t battery-powered underground loader.

The electric utility

There have been more electrified versions of diesel-powered equipment in the utility vehicle space than in any other segment of the underground mining market, and it appears this is where most mining companies start their electrification journeys.

Safescape's Bortana EV has been that entry point for Kirkland Lake Gold's Fosterville gold mine, in Victoria, Australia.

The vehicle uses the chassis of a diesel-powered Agrale Marruá, with **3ME Technology** supplying the system integration expertise and component supply, and Safescape providing the design and engineering expertise. Officially launched last year, the Bortana EV has since made its way to one of the world's most profitable gold mines for a trial.

Safescape Managing Director, Steve Durkin, told ***IM*** that the company has learned a lot from the trial, "with continuous tweaking of operating software and a few hardware improvements to facilitate maximum capability of the vehicle".

During the three-month testing period, the Bortana EV has been used in the roles of "production shiftboss" and "development shiftboss ute" and it has simulated service crew, nipper and bomb ute cycles, Durkin explained.

The Bortana EV uses the chassis of a diesel-powered Agrale Marruá, with 3ME Technology supplying the system integration expertise and component supply, and Safescape providing the design and engineering expertise

Most of these trials occurred when the company had a 415 V onboard charger installed and, as such, the vehicle could only be charged on the surface, he said. "While we were able to complete full shifts in the shiftboss role without charging, we were unable to complete full shift cycles for the heavier use case roles."

Charging underground could provide a very different dynamic, reducing the impact on the work schedule for operators if the vehicle had a 1,000 V charger on board, Durkin said.

The company has since installed such a system, meaning it can charge from any jumbo or pump box installed throughout the mine, he said, explaining that there is no longer a requirement to stop the vehicle specifically to charge it.

"Operators are now able to place the vehicle on charge when they park it at any suitable opportunity throughout their shift," he said.

The trials at Fosterville were primarily to test whether the vehicle could achieve typical mining duty cycles and to test two motor configurations and charging configurations. The extreme conditions of underground mining also enabled Safescape to shake out a few software bugs to improve the driving experience, Durkin said.

The company is currently talking to several mines in Western Australia to arrange trials with the prototype in the first half of this year, with production vehicles starting to be delivered in the September quarter, Durkin said.

3ME, meanwhile, has signed a distribution deal with KESHI Group that will see its e-mobility solutions equipped with flameproof electric motors. The 10-year agreement comes as 3ME continues to build its strategic position in the mine electrification sector.

KESHI Group, through collaboration with UQM Technologies (now Danfoss Editron), developed a flameproof electric motor designed to meet explosion-proof compliance, and 3ME, through its connections with UQM Technologies over the last 10 years, was provided an introduction to the company that led to this formalised collaboration.

The current flameproof motors include UQM internal components – named a cartridge – combined with a KESHI Group metal housing. This will be incorporated into 3ME Technology's flameproof system going forward.

Expect to hear more from 3ME Technology in the near future, with the company set to present at ***International Mining Events'*** *The Electric Mine 2020 conference* this month and new technology and OEM partnership updates on the cards.

Still on utility vehicles, **Hermann Paus Maschinenfabrik GmbH** has been making waves in Europe with its electrically driven MinCa 5.1 E passenger vehicle. Debuting at the most recent Bauma, the machine is based on the diesel-driven MinCa 5.1 and is designed to "meet the needs of tomorrow's deep underground mines".

As with all fully electric vehicles, the MinCa 5.1 E produces no exhaust emissions, reducing the ventilation burden and improving conditions for personnel working underground.

The MinCa 5.1 E measures 4 m x 1.95 m and can carry a payload of approximately 1.2 t, making it well suited for use in narrow vein mining or tunnel construction. A 90° turn can be driven within a roadway width of only 2.9 m – another boon for narrow vein miners – while it can reach a speed of up to 30 km/h on straight tracks. It can be equipped as a passenger transporter for up to five people with space for equipment, or as a repair vehicle, Paus says.

With the MinCa 5.1 E's nickel-manganese-cobalt-oxide battery chemistry and appropriate charging technology, the machine can be charged to 80% of its capacity in just half an hour, according to Paus, with the battery pack located at the rear of the vehicle.

The Paus MinCa 5.1 E can handle inclined ramps up to 45°

The capacity "under the hood"" can be extended by a further 50 kWh, according to Paus. "This gives the mines the opportunity to increase the MinCa 5.1 E to 100 kWh capacity, enough for an eight-hour shift even under the toughest conditions," it says.

It can also drive up to 20 km/h uphill, with the high torque meaning ramps of up to 35% are no problem, Paus said. With the optional onboard charger, it is possible to charge at any three-phase AC connection.

"Like all mining vehicles from Paus, the MinCa 5.1 E was specifically designed and built for use in underground mining," the company said. "The thickness of the materials used are specially dimensioned for underground operation to ensure a long working life. Safety aspects such as the ROPS/FOPS driver's cab are a given. Even the planetary rigid axles cannot be compared with adapted road vehicles – they are much more durable. The MinCa 5.1 E also features a four-wheel drive system to handle rough roads and inclined ramps up to 45°."

Earlier this year, Canada-based **Marcotte** was amalgamated with **Timberland Equipment Ltd**, with the Ontario-based group inheriting a range of BEVs. This includes the electrically-driven RAM 40 platform with cassette system that is able to lower the capital cost of fleets. This platform features

Above ground developments

Thanks to Boliden's recent trial at its Aitik open-pit mine, in Sweden, the subject of surface mining trolley assist is back on the industry's agenda.

Offering environmental and productivity benefits, trolley assist technologies have been spoken of for decades. In the height of the oil crisis of the 1970s, numerous studies examining applications were completed and miners made preparations to reduce their reliance on diesel.

Despite this, widespread industry adoption has not occurred.

ABB, which supplies not only batteries, drives and motors for battery-electric equipment, but can also provide the infrastructure required for trolley assist projects, believes the market is about to turn once again. Gunnar Hammarström, Global Product Manager Trolley Electrification Systems for ABB, thinks there are three main reasons why it is about to take off.

"One is the legislation and environmental part of the business case," he told ***IM***.

Boliden, which has moved from the 700 m trolley line trial at Aitik to confirming it will install an additional 3 km of trolley line at the mine, plus 1.7 km at Kevitsa (in addition to the accompanying conversion of 13 diesel-electric haul trucks, including some of the site's new **Komatsu** 830Es), says it will reduce its diesel consumption by 5,500 cu.m/y when its investment is complete. That is a big number.

"Another completely different reason for why demand has been picking up, especially for larger trucks, is there are a lot of diesel-electric trucks coming into mines," Hammarström said. These trucks already have an electrical system on board to tap into, which makes it easy to put them on a trolley line.

Lastly, the volatility of fuel prices has had an impact, according to Hammarström. This is leading miners to diversify their energy mix to help reduce and stabilise input costs.

When added to the productivity gains that can be achieved with trolley assisted haul trucks and the reduction in noise when trucks run on this line, it is hardly surprising Boliden is not the only one charging into trolley assist.

In the last year-and-a-bit, First Quantum Minerals has said it will equip its Cobre Panama copper-gold mine, in Panama, with trolley assist, while Austria iron ore miner, VA Erzberg, has announced it intends to electrify the main haul road of its Erzberg mine site and operate a fleet of T 236 trucks from 2021 under trolley assist.

On top of this, RNC Minerals has said it is studying the use of trolley assist at its Dumont nickel-cobalt project in Quebec, Canada.

While trolley assist has been used long before the mine electrification phenomenon we know today gained traction, Hammarström sees it helping facilitate this market move.

"Generally speaking, I think for most of the vehicles you have in a mine, you can go on battery, but it is very far into the future where you have major uphill transportation of all your production in the mine through batteries," he said.

The technology involved with stationary charging and the ability to re-charge the battery when going downhill would need to improve on the biggest haul trucks to make it a viable proposition, he explained.

"Yet, if you look into the future – and not that far – a diesel electric trolley might be an intermediate phase," he said. "If you have invested in trolley now, you can certainly use it when you have batteries (driving the trucks)."

This could see battery-powered haul trucks carry out tasks 'off-line' when going downhill or on a flat before they 'attach' back onto the line for uphill transportation of material where the battery can be recharged.

ABB is not the only company thinking trolley assist has a big future in open-pit mining.

One of its partners on the Aitik trial, Caterpillar, has recently commercialised its trolley assist system for Cat electric drive mining trucks. The move should allow mining operations to reduce carbon emissions, lower fuel and engine costs, and boost speed-on-grade for greater productivity, it said.

The Cat trolley assist retrofit kit is currently available for the 795F AC truck, with the trolley design compatible with three other Cat electric-drive mining trucks, namely the 794 AC, 796 AC and 798 AC.

During the nearly two-year pilot project at Aitik, four 795F AC trucks were used on the 700 m electric trolley line and, according to Jonas Ranggård, a Program Manager at Boliden, availability has been high despite the arctic conditions.

"There are few projects that can show both environmental and productivity improvements of this magnitude," he said. "This is why Boliden has decided to expand the trolley infrastructure in Aitik and equip its entire 795F AC truck fleet with trolley assist systems."

Eric Ruth, Electrical Senior Product Team Leader with Caterpillar, said: "We feel that trolley assist can play a role in achieving mining companies' greenhouse gas reduction goals. Simultaneously, trolley assist boosts productivity by increasing speed-on-grade. In fact, testing at Aitik mine has shown that a 795F AC equipped with trolley assist is the most powerful mining truck in the world!"

The trolley system significantly reduces diesel engine emissions at the mine via substitution of electricity during the most demanding part of the truck work cycle. Powering a 337 t payload 795F AC via trolley on a 10% grade as it climbs the ramp out of the pit saves up to 40 litres of diesel fuel per kilometre of trolley line, according to Cat. Fuel and engine costs, meanwhile, are reduced by more than 90% while the truck is on trolley.

The trolley system also boosts productivity. Operating with trolley assist, speed-on-grade increases as much as 100% versus diesel-only mode, Cat said. Using trolley, a loaded 795F can run at 28 km/h on a 10% physical grade with solid haul road conditions.

several cassette options such as a scissor lift, fuel & lube and ANFO loader.

Timberland said: "The RAM40 was designed with better sightlines and increased visibility around the machine, making it safer for the operator and everyone working near the equipment. In addition, all maintenance activities can be performed from ground level, allowing easier maintenance and daily checks. A standard carrier means common parts allowing for better service and support, along with quicker build times for new capital orders."

Timberland Equipment says its new BEVs offer a "true" battery powertrain without the need for mechanical components. This reduces wear on the machine and greatly extends the amount of time between routine service intervals, according to the company.

Driven by design

There is clearly a plethora of electrification options available on the market and, in the next decade, there is likely to be even more as developments seen underground become more prominent in surface mining.

Yet, just as diesel-powered mining fleets are made up of different types of machines to suit the environment in which they operate, there will be variety to the decarbonised fleets of the future.

MacLean's Marshall concluded: "It very much depends on the geometry of the orebody; that is what drives a lot of your decisions about how you are going to use energy in that mine. It is based on horizontal width and vertical height. That creates the energy profile of how you expend energy.

"Some mine geometries will not be able to be mined purely on battery, but there are plenty that can.

"Each mining company will seek to work with their OEMs to adequately design an energy and operating strategy that works for them."