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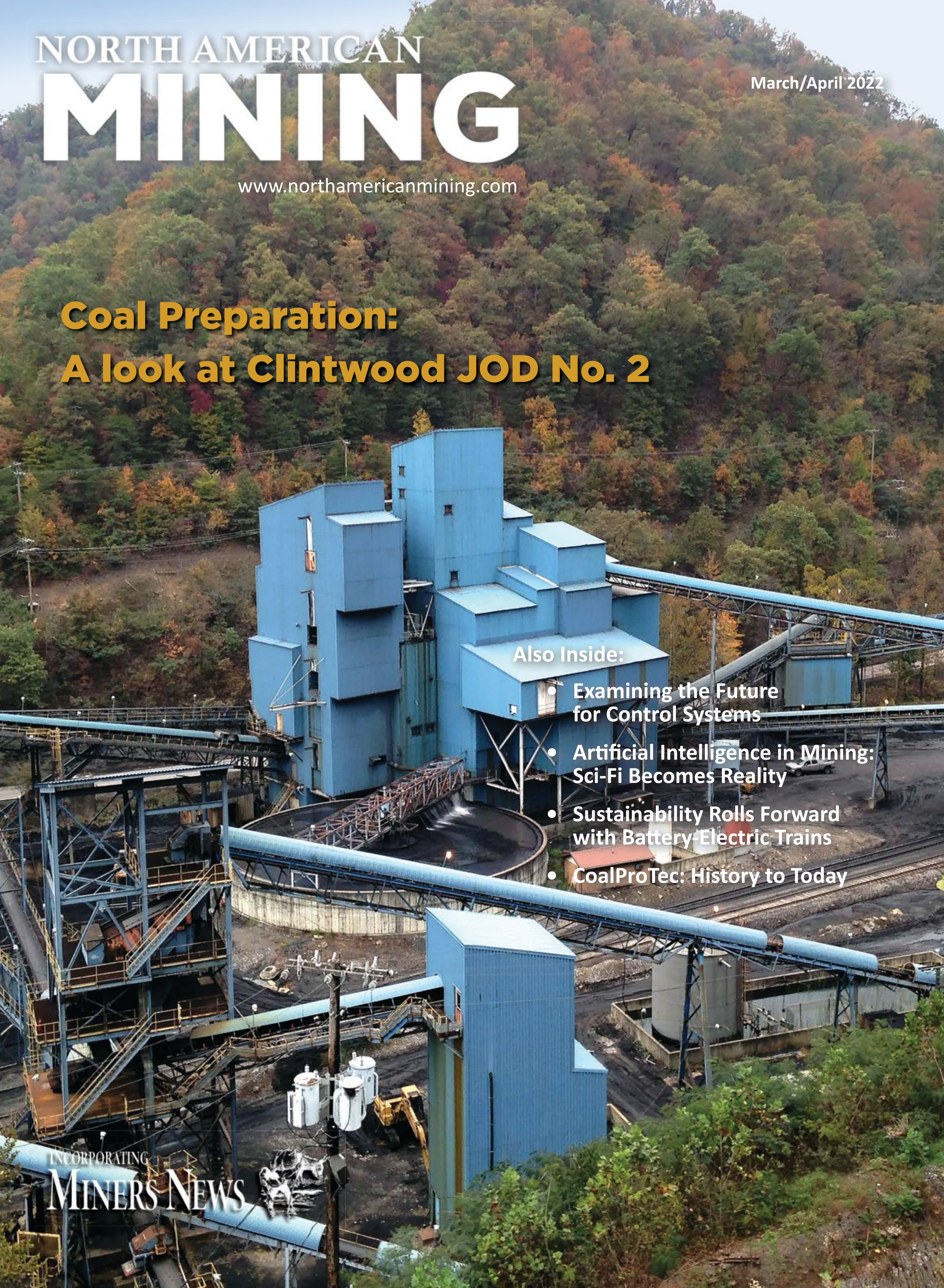

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Advanced process control for ore processing improves throughput, efficiency, and sustainability

Optimizing all the variables related to comminution and separation requires sophisticated control strategies.

By Devin Marshman, Spartan Controls and David Harrach, Emerson

Ore processing operations connected with mining sites are a critical but costly step in the larger effort to produce refined metals. Regardless of the final purification process, ore must be prepared to meet refiner composition specifications, create optimal particle size, support preliminary separation, and impart other characteristics necessary to ensure efficient final separation, whether by chemical means or traditional smelting. Steps can involve grinding, screening, thickening, flotation, and others to achieve the desired intermediate product.

These steps depend on automated process control to maximize recovery of on-spec product in a cost-effective manner. Grinding operations are generally the most energy intensive steps of a processing plant, often consuming up to 10 kilowatt hours per ton of ore processed. Selecting the most effective control strategies for this and other processing equipment is the subject of much discussion at many mining companies given the enormous stakes involved.

The ability to shave even a few percentage points off total energy consumption per ton can result in huge increases to a facility's bottom line, along with substantial improvements to efficiency and sustainability.

Advanced process control (APC) strategies are becoming increasingly critical to ore processors, but there are different approaches under this umbrella. Process designers must consider carefully which to adopt, whether from the most current APC options, or more traditional approaches.

Understanding process control

To put this discussion into context, it helps to think about some basic concepts of process control automation, and how it can be applied in ore processing applications.

Regulatory Control – This traditional method, which relies primarily on PID-based loop control, is the most basic building block of automation (Figure 1), and there will undoubtedly be many small controllers throughout a facility

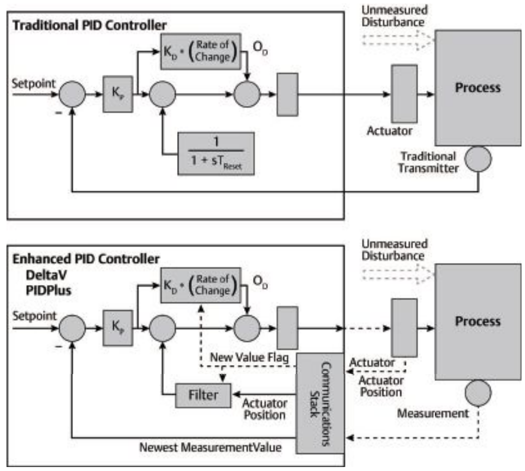


Figure 1: Basic regulatory control drives many simple processes but can't handle all the complex operations of ore processing.

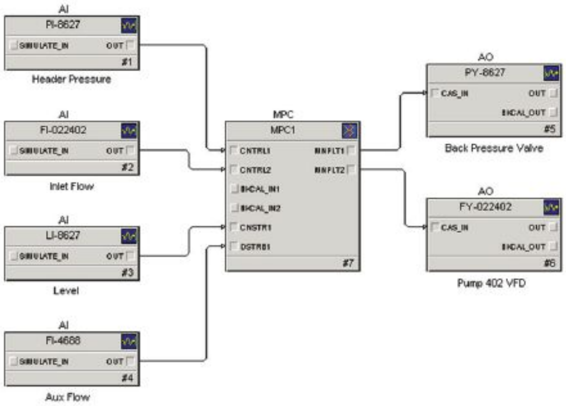


Figure 2: MPC can handle multi-variable applications far better than regulatory control, but it still has critical limitations.

using this approach. A sensor measures a process variable and compares it to a setpoint. If the variable deviates from the setpoint, it adjusts an actuator to bring it into line. For example, to control liquid flow, a flow meter provides the process variable, and a control valve is the actuator, changing its position as needed to bring the actual flow into line with the setpoint. The system response can be tailored by adjusting the proportional, integral and derivative parameters – but this method of control is often not sufficient.

This approach can be very effective for appropriate applications, but it has serious limitations. First, it can only handle one thing at a time because each process variable must be paired with a single and distinct point of actuation. Where there are multiple variables related to the same application, designers may try multiple loops in sequence, in parallel, or loops within loops, but these can get complex and difficult to control.

Second, regulatory control is reactive in nature, making an adjustment only when the variable moves out of range. It can't anticipate a change, so if the process is slow moving, it may not be able to respond quickly enough to avoid an excursion into an undesirable range.

Model Predictive Control – Model predictive control (MPC) takes a different approach, and it can be applied to simple and complex multi-variable challenges. It creates a mathematical representation of the process (Figure 2), quantifying the various inputs necessary to achieve one or more desired outputs. For example, reaching a given ball mill load might require specific inputs of feedstock flow, water flow, mill speed and other variables. The model will determine what all those inputs must be to achieve the specified output, and then adjust those inputs accordingly.

This approach has gained popularity for ore processing because it can handle complex operations where there are multiple potential variables. Under operating conditions where the process is generally stable and changes are gradual, MPC can be effective, so it should be in a designer's toolbox. However, it also has potential pitfalls.

First, it is only as good as its model. If stoichiometric or physical relationships are not characterized correctly, the controller will not respond correctly and may drive the process out of the desirable range. Once this is recognized, the model can be adjusted, but it is not always easy to recognize where the problem lies. Any time there is a change in the equipment or process, including a critical feedstock characteristic, the model must also be adjusted, complicating what would normally be considered a simple change. Some of the most frequent adjustments, such as feedstock characteristics, could be built into the operator's human machine interface, but adjusting for equipment changes might be more difficult. Non-linear aspects of the process make this particularly challenging toward the high or low extremes of any variable.

" The ability to shave even a few percentage points off total energy consumption per ton can result in huge increases to a facility's bottom line, along with substantial improvements to efficiency and sustainability. "

Second, MPC is a finite-horizon controller, which means that its goal is smoothly and gradually bringing the process to its optimal setpoints at some given point in the future. In doing so, MPC avoids large or sudden changes to its points of actuation, preferring to gradually ramp them instead. Without extremely specialized tuning, MPC does not have the same "proportional kick" in response to upsets or setpoint changes that you can achieve with PID.

In practical operation, MPC is best where the controller can move the process to its comfortable operating level and keep it there. But where there are frequent and potentially drastic changes caused by an upset, such as in a SAG mill, MPC may not be able to respond quickly enough. Unstable situations

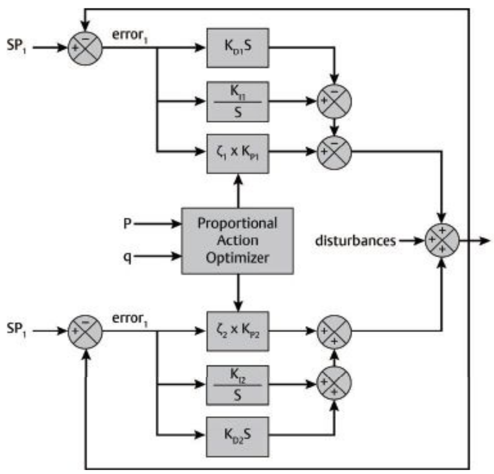


Figure 3: IQC has the multi-variable capabilities of MPC and adds the benefits of traditional regulatory control.

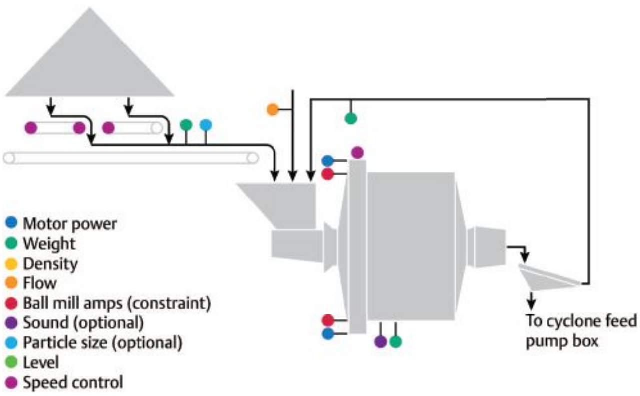


Figure 4: To achieve maximum throughput with minimal equipment wear-and-tear, IQC balances multiple variables, while responding quick-

call for a strong proportional action, where the controller responds to a rapid change with a rapid and strong correction. MPC can struggle in such situations.

Integrated Quadratic Control – Integrated quadratic control (IQC) is a newer method of closed-loop control, and its use is growing rapidly for ore processing applications. It is a single-input, multi-output controller (Figure 3), that uses velocity-form quadratic optimization to split the output signal. This allows it to control multiple functions simultaneously, even to the point of adjusting and optimizing its strategy where it has multiple options to achieve the desired setpoint.

For each control output, IQC defines two sets of operating limits: one normal high and low limit, and one extreme high and low limit. It then characterizes the process by determining how far it can push the controller outputs within the normal operating range to meet the controller setpoint, up until the controllable variables are saturated.

However, if all control outputs are saturated and IQC cannot reach setpoint within the normal operating range, it will expand the limits to the extreme values. The extreme values are defined as hard limits, and they are typically only used during upset recovery or abnormal operation. Controller gains are automatically modified in this extreme region to address the nonlinear behavior of abnormal operation. IQC can also automatically adjust the proportionality of its control efforts to chase major setpoint adjustments or process upsets quickly, allowing it to reoptimize outputs with minimal lag time.

Applying IQC

IQC can be applied in many processes, but there are two areas of ore processing where it has been particularly beneficial: SAG mills and flotation separators.

SAG mills (Figure 4) are a critical step in the process, but for many ore processors, they are also major headaches:

- A frequent bottleneck, responsible for constraining overall throughput.
- A facility's biggest energy consumer.
- Difficult to control due to feed variability.
- A frequent source of trips, originating from multiple causes, which can interrupt production.
- Costly to maintain with expensive liners that wear rapidly when misused.

Operators must monitor, and sometimes adjust, a long list of variables, including:

- Motor power, which might be constrained by available amperage limits.
- Mill speed.
- Input flow rate and feedstock characteristics.
- Recycled product weight and characteristics.
- Total weight and density of product in the mill at any given time.
- Water input.
- Downstream inventory and processing capacity.

" It's common to find comminution accounting for more than 50% of overall energy consumption and 10% of total production cost, so the ability to move the cost needle in this area has enormous impact. "

These must all be balanced carefully to ensure maximum throughput with optimized particle size, while avoiding, or at least accommodating, sudden feed-rate changes. Operators must also monitor power consumption and operate in a way that maximizes liner life. Clearly, balancing all those variables

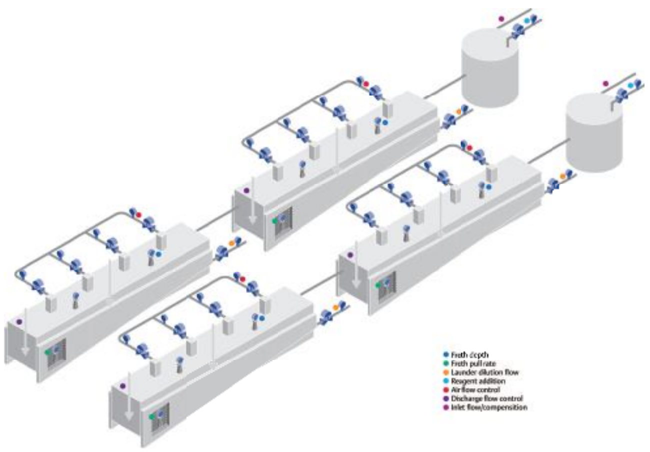


Figure 5: Flotation separators require integrated control since a change in just one of the many variables can cause production disruptions.

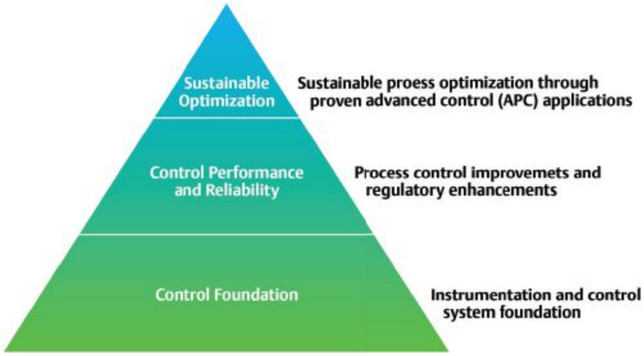


Figure 6: Sustainability programs depend on improving all phases of a manufacturing facility to increase efficiency.

calls for very responsive and sophisticated process control, which is possible using IQC.

Flotation separators (Figure 5) present challenges related to their multiple-input and multiple-output variables, which must be controlled simultaneously. This is especially difficult because the pull rate from each cell along the flotation bank may not have its own flow rate measurement. IQC's multi-output optimization within a defined normal operating region addresses this problem by ensuring that all cells move together, rather than compensating for flow rate changes by throttling a single cell.

Immediate response to feed changes is another critical aspect of effective flotation operation. Product recovery rates can change significantly during upsets if cell air, level, and reagent addition are not also adjusted to match. Even temporary upsets to the flotation cell can quickly lead to off-grade product, contaminated tailings, or sanded-out cells.

The IQC controller must automatically coordinate multiple variables across each cell within a bank to maintain safe and stable operating conditions, including cell level and pull rate, reagent (e.g., flocculant) addition rates, and air injection rates.

By coordinating the above variables to maintain ideal concentrate pull rates, IQC can effectively control flotation under a wide range of operating conditions. Once this has been achieved, supervisory optimization can be added to coordinate target pull rates on various flotation banks at the site to maximize net product recovery based on final product grade and available processing capacity.

Approaching APC upgrades

The two applications just discussed are not the only areas that can benefit from IQC. Others may not be as complex, but they can also be critical to improving overall facility performance. The list can include thickeners, clarifiers, pH control, pump-box level control, grade control, and multi-pump applications. When making evaluations, a company must consider the criticality and complexity of each, and then apply the correct control strategy.

Many facilities look at the range of applications individually and select separate controllers for each, trying to tailor the solutions, one-by-one. This can work, but it creates a fragmented environment requiring extensive manual coordination. A more practical alternative is to choose one large-scale automation host system that can support multiple control strategies and coordinating the entire operation.

APC and sustainability

This approach is especially important as mining companies, along with virtually every other industry, are coming under increasing pressure to meet sustainability goals. How these are defined and realized vary from company to company, but generally involve reductions of carbon footprint, manifested as lower energy consumption overall and reduced fossil fuel use. As a practical matter, companies can make significant advances via better internal energy management and making processes more energy efficient. Effective control helps accomplish both.

Successful sustainability improvements over time generally come as the result of tightening up the entire operation, often starting with improved process control strategy (Figure 6). Effective control, especially when APC is in use, depends on top-notch, well-maintained instrumentation. Without reliable process measurements and effective actuators, APC can't tame complex operations.

Comminution processes are especially important in this effort since they represent the largest single energy use in the entire mining process. It's common to find comminution accounting for more than 50% of overall energy consumption and 10% of total production cost, so the ability to move the cost needle in this area has enormous impact.

Mining operations can support sustainability efforts by working with a qualified partner organization capable of understanding the full scope of such a program, with the experience needed to guide planning and implementation. With effective strategy is combined with well-chosen automation technologies, improved sustainability will result, along with increased profitability.

Editor's note: All figures courtesy of Emerson.

Diesel–less future?

The mining industry has long relied on diesel. Cleaner alternatives are however needed if the industry is to successfully decarbonize its mine sites.

By Jonathan Rowland

The phrase "net zero mining" is fast taking its place in the dictionary of 21st century mining buzzwords, just after the "digital mine" and slotting in ahead of the related term, "sustainable mining." But as with most buzzwords, it's often used with only vague concern over what it actually means. To begin an article about any aspect of net zero as it relates to mining, it's therefore important to set some context.

Establishing what proportion of global greenhouse gas (GHG) emissions is generated by the mining industry is a good starting point – but it is harder said than done and is again subject to difficulties in definition.

For example, the mining process itself produces limited GHG emissions. About 0.01 tonnes of CO_2 (tCO_2) are emitted per tonne of iron ore extracted; a further 2.19 tCO_2 per tonne of finished metal are, however, emitted when refining that ore into steel. The discrepancy between the mining of bauxite and production of finished aluminum is even greater.[1]

Although most estimates of GHG emissions from mining include primary processing, the weighting of GHG emissions so heavily toward refining and smelting operations is an important one to note. Improvement here will have much more impact in terms of emissions reduction than anything that happens in the pit itself. It's also relevant to note that, although carbon emissions are generally the focus of global environmental action – and media coverage of it – in mining they are only (and perhaps not even the most important) aspect of environmental sustainability.

The use of water is at least as pressing, and often much more so within the local context.

A final word of introduction relates to the different types (or scopes) of GHG emissions:

- Scope 1 covers direct emissions, e.g., from the running of mining vehicles or the on-site (off-grid) generation of electricity;

- Scope 2 covers indirect emissions, e.g., from the generation of electricity purchased from external suppliers; and
- Scope 3 covers all those emissions produced along the supply chain – from the manufacture of mining and minerals processing equipment to the use of the finished products.

Net zero pledges – at least those with defined targets – most often focus on Scope 1 and Scope 2 emissions, since these are the easiest for companies to influence, although strategies to reduce Scope 3 emissions are now being developed.[2]

What about mining trucks?

This preamble should help set emissions from mining trucks into the wider context. Even combining both Scope 1 (from the combustion of diesel) and Scope 2 (from the supply of that diesel) emissions, the roughly 52,000 active mining trucks[3] nevertheless contribute only a very minor part of wider global GHG emissions. Yet abating those emissions must be a part of any mining company's net-zero strategy, as Verónica Martínez, project lead of the Innovation for Cleaner Safer Vehicles program at the International Council on Mining and Metals (ICMM), explained to North American Mining.

According to Martínez, "when you start analyzing the emissions profile of mining operations, about 50% of direct (Scope 1) emissions come from the use of diesel in mining trucks. In specific regions, such as Chile, this number goes up to 80%." When it comes to specific mining companies and their journeys to net zero, mining trucks are therefore a "very relevant source of emissions."

A key initial step along this road relates to fuel efficiency. Fuel consumption depends on a range of factors – from truck load, speed, power and weight (empty and loaded) to acceleration, idle time, fuel quality, aerodynamics, road surface and grade, tire quality, alignment and inflation, weather and climate, truck condition and even the truck driver's driving style.[4] A 300-t truck may consume about 4,000 liters/day of diesel, but when that fuel is consumed through the day is therefore not consistent – as Martínez noted: "If you are coming out of the pit, fully loaded, that's 70% of your fuel consumption."

As a result, new technologies that can be retrofitted to existing fleets and that target the most fuel-intensive moments in truck operations can make a big initial difference, without the investment required to implement an entirely new fuel ecosystem.

At Boliden's Aitik copper mine in Sweden, for example, existing mining trucks have been adapted to run with an electric trolley assist system out of the pit. The trolley line not only helps to reduce GHG emissions; it also improves the speed of the loaded trucks up-grade, thereby increasing mine productivity.

After a successful trial, the original 700-m route is being extended to cover some 3 kilometers of the mine site and is also being rolled out on a 1.8-km stretch of road at the Kevitsa nickel mine in Finland. The company expects to save 5.5 million liters of diesel a year when these systems are complete.[5]

Low-carbon fuels, such as B100 biodiesel, offer another option when it comes to decarbonizing existing fleets, although this option is contingent on the availability of optimized engine designs, the ability of mines to obtain B100 (without increasing their Scope 2 emissions), and the competitiveness of the cleaner fuel compared to traditional diesel.

"Mining companies will buy new mining trucks depending on their fleet replacement cycle, which is very site-specific.

Liebherr offers trolley assist systems for most of its haul trucks. (Photo: Liebherr)

We therefore need to understand how to reduce the emissions of existing fleets. What are the technology pathways for this? Although they won't get us to zero, they will allow us to significantly reduce emissions in a much quicker timeframe than relying on largescale capital investment in new vehicles," said Martínez.

Transformational technologies: electrification

To reach net zero,xs mines will have to think outside existing technologies. There are numerous options here, notably hybrid and battery electric vehicles (EVs) and hydrogen-based systems. These will, however, require the adoption of new energy paradigms at both mine site – and more broadly. The electrification of mine trucks, for example, mirrors the electrification of the wider transport network in society in terms of its reliance on suitable battery technology (and the sustainable production thereof) and effective charging infrastructure.

Tackling that latter challenge, the Charge on Innovation Challenge, founded by BHP, Rio Tinto and Vale, and facilitated by AustMine, is asking technology supplies to develop scalable, interoperable solutions that are capable of delivering 400 kWh of electricity to a 200-t battery EV in a way that "maintains or improves current productivity levels, without adding time to haul cycle."[6]

The number of challenge partners now numbers 21 mining companies, and 21 vendors have been shortlisted to progress past the initial phase. These include both established players, such as ABB, Hitachi and Siemens, as well as new entrants like BluVein, a joint venture between Swedish clean tech pioneer, EVIAS, and Australia-based Olitek that is already catching the attention of some big names in the mining industry.

Major truck manufacturers are also actively taking up the challenge. Caterpillar has announced a number of strategic alliances to develop zero-emissions mines. These include heavyweights BHP, Rio Tinto, Teck and Newmont alongside smaller players like Nouveau Monde Graphite, which is aiming to power its Matawinie graphite mine with zero-emission machines by 2028.

BHP and Rio Tinto are also among the founding partners of Komatsu's GHG Alliance, alongside Codelco and Boliden. Announced in August 2021, the alliance will initially work to advance the company's power agnostic truck concept for a haulage vehicle that can run on a variety of power sources, including diesel electric, electric, trolley, battery and hydrogen fuel cells.

Meanwhile, Liebherr committed to offering low-carbon emission solutions, including electric drives for all trucks and excavators, trolley assist and cable reeler systems be the beginning of this year.

It also signed an agreement with ABB at MINExpo International 2021 to explore the development of mine electrification technologies, with a focus on trolley assist systems, supporting the ultimate aim is fossil-fuel free mining equipment by 2030 at the latest.

Charging may be the most visible challenge when it comes to operative electric vehicles at the mine site, but it is not the only hurdle to electrification. As with every initiative of this type, mining EVs are only as clean as the electricity that energizes them.

"When talking about zero-emission vehicles (ZEVs), we aren't just talking about emissions at the tailpipe," said Martínez. "It has to take into account a broader view. Clean – renewable – electricity is therefore a key enabling technology of the mining industry's decarbonization strategies; it must come first. There are regions that are progressing quickly in this regard. In Chile, for example, by 2025, about 90% of mines will have renewable capacity installed. Escondida, the largest copper mine in the world, is already operating with 100% renewable energy."

Meanwhile at Nouveau Monde, the collaboration with Caterpillar is intended to "support the company's goal to fully power the site with zero carbon footprint renewable energy," Caterpillar said, with an "all-electric fleet complemented by the mine's access to clean and attractively-priced hydroelectricity." And this really goes to the heart of the matter, as Caterpillar continued: mining companies "cannot focus on one product alone to meet their objectives; they will need to consider their entire operations – from the power source, to the machine, supporting technology, infrastructure and the services."

Transformational technologies: hydrogen

A number of mining companies and suppliers are also looking into hydrogen-based technologies, such as hydrogen fuel cell EVs, which offer similar performance and range to current diesel-power ultra-class trucks. For example, as part of its FutureSmart Mining program, Anglo American is working with multinational energy service company, Engie, to develop and fuel the world's largest hydrogen-powered mining haul truck.

Engie is also working alongside research partners, CSIRO Chile and Mining3, to design and manufacture a new powertrain that allows mining vehicles to operate with hydrogen. The Hydra Project is one of three based around the use of hydrogen in mining supported by Chilean economic development agency, Corfo.[7]

Hydrogen also offers a "more integrated" approach to decarbonization for those mines not connected to the grid, according to Martínez.

"You can think of hydrogen as the carrier for energy across the mine, not just when it comes to powering mining trucks."

This has been recognized by the Green Hydrogen Consortium, which includes BHP, Anglo American and Fortescue as founding members, alongside consultancy, Hatch, is working to explore the potential for hydrogen within the resources and mineral processing industries more generally.[8]

Skepticism remains, however, over how helpful hydrogen may be, even among consortium members. Dr. Huw McKay, vice president, Market Analysis and Economic at BHP, noted in an April 2021 podcast that "it seems unlikely that green hydrogen will achieve competitive narrow or all-in costs any time soon: certainly not in either the 2020s or the first half of the 2030s.

"[But] the future has a way of surprising you, and hydrogen may yet make a considerable contribution to our 2050 net zero objective for Scope 1 and 2 and assist with the material reduction of our value chain (Scope 3) emissions generated by the transport and use of our products. The route to that end state is not visible today, but we do not completely count it out."

Komatsu's GHG Alliance is working to advance the company's power agnostic truck concept.

As with electrification, a key challenge is the sourcing of cost-competitive green hydrogen. Australian mining company Fortescue is one of those working towards a solution here, creating a spin-off company, Fortescue Future Industries, to develop a portfolio of both renewable energy and green hydrogen projects with the aim of supporting not only its own decarbonization strategy, but the decarbonization of other hard-to-abate sectors.[9]

The truck as a technology platform

What is emerging from the development work is that the nature of the truck is changing. From a single technology based around the internal combustion engine, in the future the truck is going to be a platform for a range of different technologies, which will differ from mine site to mine site, depending on local context.

"There is no silver bullet," said Martínez. "Different technologies will be required. We should therefore be thinking of the truck as a platform into which we can plug a range of technologies, depending on the needs of the mine and the local context – for example, the availability of clean renewable energy or onsite green hydrogen."

It's a concept that has been picked up by the truck manufacturers, as exemplified by Komatsu's fuel-agnostic truck. For its part, Caterpillar confirmed to North American Mining its approach, stating, "A variety of solutions will be needed for customers and their specific job sites."

Oliver Weiss, executive vice president for R&D, Engineering and Manufacturing, at Liebherr Mining Equipment was perhaps most eloquent on the topic, however. In an article for Liebherr's in-house magazine, flexibility, he argued, is the only way forward.

The "future portfolio of solutions will be less electric grid dependent, providing more flexibility and will likely be based on a combination of technologies," he said.10 "Flexibility is provided through on-board energy storage with the use of batteries or renewable fuels, such as hydrogen or hydrogen based derivate fuels (ammonia, methanol or more sophisticated e-fuels)."

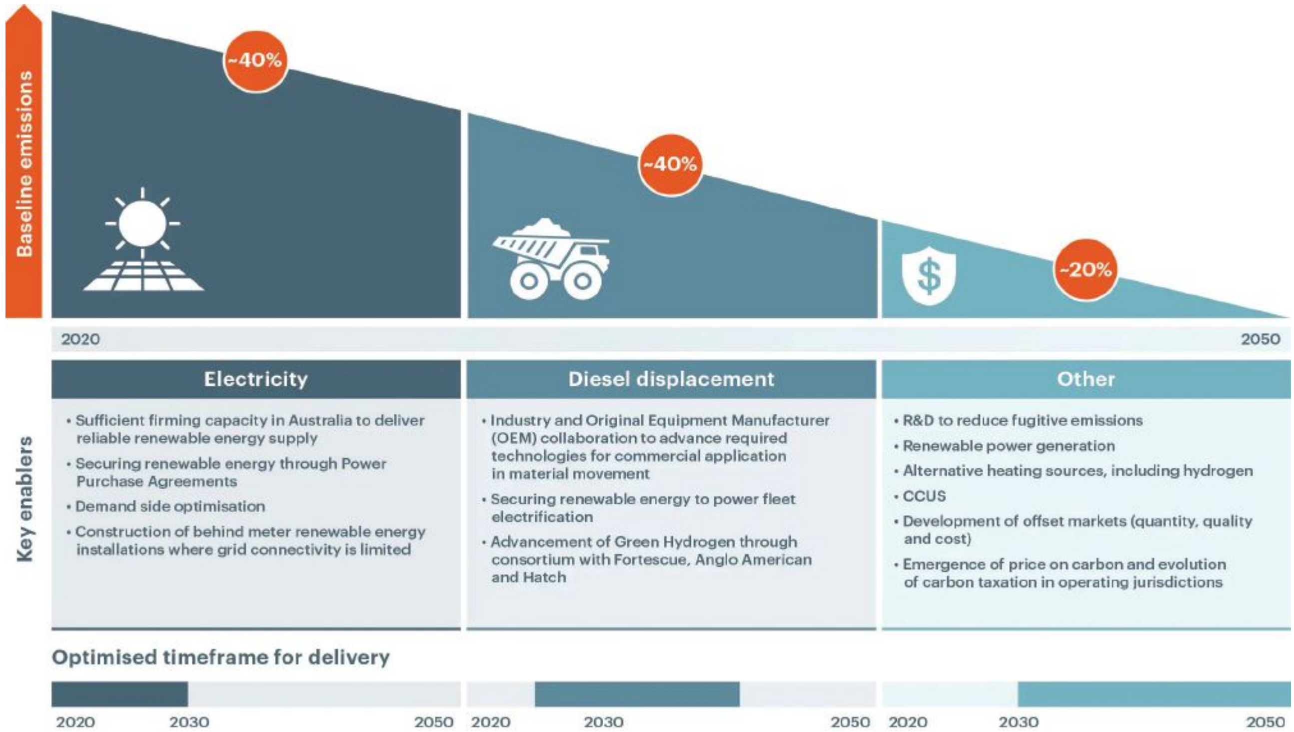
Weiss continued in an optimistic vein, noting that, "methanol combustion […] is ready to move towards serial engine industrialization based on market demand [while] hydrogen combustion engines are currently being tested in our factory in Switzerland. [We also see] high potential in the usage of ammonia for heavy mobile, high energy demanding machines." In addition, when "more sophisticated e-fuels become competitively available at large scale, Liebherr is ready to utilize these fuels in machines equipped with Liebherr engines."

This positive attitude is mirrored more broadly through the industry, said Martínez.

"We're seeing an acceptance that this is possible with companies creating partnerships for trialing and testing. But this is the key challenge now: how do we get to the trialling and testing phase faster? Do we need to bring in investors or other actors to accelerate progress? Are there key jurisdictions that might be more suited to move into early adoption?"

These are questions that ICMM is grappling with as it works with companies to facilitate change in this space – but the progress made is already impressive. "The ambition of the Innovation for Cleaner Safer Vehicles program is to make zero-emission solutions available by 2040, and we are seeing partnerships between ICSV participants that are helping to accelerate the development and adoption of such solutions," said Martínez.

One tool that has helped to support this progress is the ICMM's Maturity Framework (icsv.miningwithprinciples.com/



BHP pathway to operational decarbonization. The company is already involved in multiple development activities that offer potential pathways to decarbonizing its fleet of mining trucks. (Figure: BHP)

ghg-maturity-framework), which helps mining companies understand where they are today, compared with where they want to be. It has also created a common language around zero-emission trucks that is vital for collaboration.

"The framework has been used by member companies to self-assess over 100 mine sites globally," explained Martínez. "Now these companies are in a position to develop their own roadmaps, identifying what partnerships are needed, what capacity they need to make available. For example, BHP has its fleet decarbonization snapshot, which starts with trolleys then moves to batteries and widespread adoption. We have moved from a place where decarbonization of mining trucks was wishful thinking to now thinking about practical implementation."

A solvable challenge

As with all areas of the mining industry's sustainability journey, there are challenges ahead. But zero-emission trucks – albeit representing only a small part of the grand picture of carbon emissions reductions – now appears to be a challenge that not only can be solved but will be. And relatively soon. This makes it a potentially important example for other, more intractable, challenges, as Martínez concluded.

"We're positive that change can now happen. It's a good example for other areas of the new-zero transition, showing how collaboration over a problem can lead to practical partnerships that accelerate change. It's an important lesson to learn as we start to think about the bigger challenges, particularly those associated with Scope 3 emissions."

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