Volume 23 | Issue 1 | February 2026

MINING & QUARRY WORLD


ENDURON®

Volume 23 • Number 1 • February 2026

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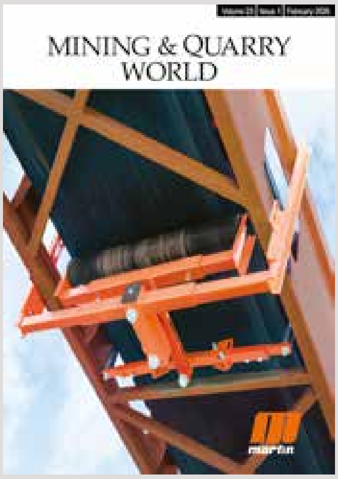

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Published by: Tradelink Publications Ltd.
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E-mail: admin@mqworld.com
Web: www.mqworld.com

All subscriptions payable in advance.

Published 6 times per year, post free:
UK: £60.00 **Worldwide:** £70.00 | ISSN No: 2045-2578 | D-U-N-S No: 23-825-4721

US-backed Brisbane miner targets billion-dollar float

RZ Resources, already in the global spotlight as a key US critical minerals supplier, is plotting an ASX float that could be worth $1 billion.

As reported by the Australian Financial Review, the mooted float would underscore surging global demand for Australia's critical minerals sector, turbocharged by last year's $US8.5 billion strategic pact between the United States and Australia aimed at securing supply chains outside China.

RZ Resources – one of seven Australian developers identified by the White House as potential suppliers of critical minerals to the US – plans to use IPO proceeds to restart its mothballed processing plant at Pinkenba in Brisbane and advance its Copi mineral sands project near Mildura in Victoria's Murray Basin.

Copi is expected to produce rutile, zircon, ilmenite and monazite, with product destined for customers in Japan and the US. Rutile is a key input for titanium, which is critical to aerospace and advanced defence manufacturing.

Crucially, the integrated project would allow RZ to mine, process and export directly to end users, bypassing China, which currently dominates global critical minerals processing.

The company rose to prominence in October after receiving a letter of interest from the US Export-Import Bank (EXIM), signalling potential financing of up to $US460 million under Washington's push to build a strategic critical minerals stockpile known as Project Vault.

"The EXIM letter of interest raised our profile and market confidence in us," RZ founder and executive chair David Fraser told the Australian Financial Review. "These types of announcements are telling the market that they've got to get into critical minerals."

RZ has also secured strong Japanese backing, including a $15 million strategic investment from Marubeni Corporation and earlier support from JX Advanced Metals, reinforcing Copi's geopolitical and commercial credentials.

The investment by Marubeni follows the investment made by another Japanese company, JX Advanced Metals Corporation, announced in June this year.

Marubeni is a major Japanese industrial conglomerate with extensive interests in the mining and resources sector globally.

Komatsu to expand North American remanufacturing with asset acquisition

Komatsu has announced plans to acquire the assets of SRC of Lexington, a Kentucky–based supplier of remanufactured components and parts for construction and mining equipment.

The transaction is expected to close by the end of February 2026, subject to customary closing conditions.

The acquisition is said to strengthen Komatsu's remanufacturing capabilities in North America and support growing demand for remanufactured solutions.

By investing in a dedicated facility in the United States, Komatsu plans to enhance its ability to serve customers in one of the world's largest construction and mining equipment markets.

Demand for remanufactured components has increased alongside the expansion of the installed base of quarry and mining equipment in North America since 2010.

Over that period, Komatsu's remanufacturing business has grown significantly, with transaction volume increasing approximately fourfold from fiscal year 2010 to fiscal year 2024.

"North America is one of Komatsu's most important markets for both construction and mining equipment," said Komatsu vice president of parts and infrastructure Danny Murtagh said.

He noted that the acquisition will allow Komatsu to deepen remanufacturing capabilities closer to customers, improve responsiveness, and support dealers and end users with cost-effective solutions throughout the equipment lifecycle.

President of SRC Holdings, the parent company of SRC of Lexington, Tim Stack said the agreement reflects a shared commitment to remanufacturing excellence, technical expertise, and long-term customer support, while also providing continuity and future opportunity for the Lexington team.

Through its reman operations, Komatsu recovers used components, restores them to like-new condition, and returns them to the market with the same quality standards as new parts.

Berkeley claims $1.25bn claim from Spain over Salamanca project

Dual-listed Berkeley Energia has filed a $1.25-billion compensation claim against Spain at the International Centre for Settlement of Investment Disputes (ICSID) in Washington DC, as part of its ongoing arbitration proceedings with the Spanish government.

The company said its wholly owned subsidiary, Berkeley Exploration Limited, has submitted a memorial of claim alleging that Spain's actions against its Spanish subsidiary, Berkeley Minera España, and the Salamanca uranium project, violated multiple provisions of the Energy Charter Treaty.

Berkeley has been in dispute with Spain over permitting and regulatory restrictions affecting the Salamanca project, which it says have undermined its investment.

The memorial of claim sets out the factual background to the project and the dispute, details the legal basis for the case, and includes key witness statements and reports from independent technical, regulatory and damages experts.

Spain has until July 2026 to respond to the filing, or until October 2026 if the ICSID tribunal orders that jurisdictional issues be considered separately.

Despite the arbitration process, Berkeley said it remained committed to the Salamanca project and was open to constructive dialogue with Spanish authorities.

The company said it was ready to collaborate with regulators to seek an amicable resolution to the permitting situation and hoped discussions could resume in the near term.

Berkeley said it would continue to provide updates on the arbitration proceedings as required.

Sunrise eyes role in US critical minerals reserve

Sunrise Energy Metals has expressed confidence it will be among the companies contributing to the recently announced US critical minerals reserve strategy, known as Project Vault.

The company is developing the Syerston scandium project in central New South Wales, which is recognised as the world's largest and highest-grade scandium deposit.

Sunrise chief executive officer Sam Riggall told reporters in Washington that the company was well positioned to supply the United States with the rare earth element, which is valued for its use in high-strength, lightweight aluminium-scandium alloys for aerospace applications, solid oxide fuel cells for clean energy, and specialty lighting.

"We would expect to be part of that stockpile," Riggall said.

Sunrise also said on LinkedIn that it was "honoured" its co-chairman Robert Friedland met with US President Donald Trump at the White House as a representative of critical minerals producers for the launch of the $US12 billion strategic critical minerals reserve.

Friedland is an American billionaire, a director of Ivanhoe Mines, and the largest shareholder in Sunrise. Another substantial shareholder is Kiril Sokoloff, chairman and founder of global investment advisory firm 13D Research & Strategy.

An updated mineral resource estimate for Syerston, announced in November, confirmed the project as the world's largest and highest-grade scandium resource, with a global resource of 19,007 tonnes at an average grade of 414 grams per tonne. This represented a 98% increase in contained scandium.

Sunrise last year received a letter of interest from the Export-Import Bank of the United States for up to $US67 million ($103 million) in potential financing.

The support from the US export credit agency underscores scandium's strategic importance, particularly after China imposed export controls on rare earths in April 2025.

The Syerston project has been identified as a candidate for financing under several EXIM programs, including the Supply Chain Resiliency Initiative and the China Transformational Exports Program.

Why China is building so many coal plants despite its solar and wind boom

Even as China's expansion of solar and wind power raced ahead in 2025, the Asian giant opened many more coal power plants than it had in recent years – raising concern about whether the world's largest emitter will reduce carbon emissions enough to limit climate change.

More than 50 large coal units – individual boiler and turbine sets with generating capacity of 1 gigawatt or more – were commissioned in 2025, up from fewer than 20 a year over the previous decade, a research report released said. Depending on energy use, 1 gigawatt can power from several hundred thousand to more than 2 million homes.

Overall, China brought 78 gigawatts of new coal power capacity online, a sharp uptick from previous years, according to the joint report by the Centre for Research on Energy and Clean Air, which studies air pollution and its impacts, and Global Energy Monitor, which develops databases tracking energy trends.

"The scale of the buildout is staggering," said report co-author Christine Shearer of Global Energy Monitor. "In 2025 alone, China commissioned more coal power capacity than India did over the entire past decade."

At the same time, even larger additions of wind and solar capacity nudged down the share of coal in total power generation last year. Power from coal fell about 1% as growth in cleaner energy sources covered all the increase in electricity demand last year.

China added 315 gigawatts of solar capacity and 119 gigawatts of wind in 2025, according to statistics from the government's National Energy Administration.

The massive growth in wind and solar begs the question: Why is China still building coal power plants and, by most analyses, way more than it actually needs?

The answer is complicated.

China is at an earlier development stage than the United States or Europe, so it needs more energy to keep growing. If more of the nation's 1.4 billion people climb into the middle class, more will be able to afford air conditioners and washing machines.

Electricity is needed to keep China's factories humming and to meet the high power demands of artificial intelligence, a government priority as it seeks to make the country a leader in technology.

Power shortages in parts of China in 2021 and 2022 reinforced longstanding concerns about energy security. Some factories temporarily halted production and one city imposed rolling blackouts.

The government's response was to signal that it wanted more coal plants, leading to a surge in applications and permits for their construction.

That 2022-23 surge drove the big jump in capacity last year as the new units came on line, said Qi Qin, an analyst at the Centre for Research on Energy and Clean Air and another co-author of the report. "Once permits are issued, projects are difficult to reverse," she said.

Construction started on 83 gigawatts of coal power last year, the report said, suggesting a large amount of new capacity may come online this year.

The government position is that coal provides a stable backup to sources such as wind and solar, which are affected by weather and the time of day. The shortages in 2022 resulted partly from a drought that hit hydropower, a major energy source in western China.

Coal should "play an important underpinning and balancing role" for years to come, the National Development and Reform Commission, the lead economic planning agency, said in guidance issued last year on making coal plants cleaner and more efficient.

The China Coal Transportation and Distribution Association, an industry group, said last week that coal-fired power would remain essential for power-system stability, even as other sources of energy replace it.

The risk of building so much coal-fired capacity is it could delay the transition to cleaner energy sources, Qin said. Political and financial pressure will keep the plants operating, leaving less room for other sources of power, she said.

The report urged China to accelerate retirement of aging and inefficient coal plants and commit in its next five-year plan, which will be approved in March, to ensuring that power-sector emissions do not increase between 2025 and 2030.

"Whether China's coal power expansion ultimately translates into higher emissions will depend on … whether coal power's role is genuinely constrained to backup and supporting rather than baseload generation," Qin said.

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MINING & QUARRY WORLD

Hillhead 2026

A jolt to heavy haul for BHP's Pilbara operations

Australia's first purpose-built battery-electric locomotives have arrived in the Pilbara, marking a major step toward decarbonising heavy-haul mining rail.

Late-2025 saw Australia welcome its first purpose-built battery-electric locomotives with BHP paving the path in Western Australia's Pilbara region.

The arrival represents a sign of the major steps forward for heavy-haul rail innovation through a combination of cutting-edge technology and a clear focus on reducing emissions and improving efficiency.

The locomotives were delivered in partnership with Wabtec, with the two fully battery-powered units to be trialled in BHP's iron ore rail routes connecting Pilbara mines to Port Hedland.

BHP Western Australia Iron Ore (WAIO) asset president Tim Day said it was incredible to see the battery-electric locomotives arrive in Port Hedland, referring to them as the culmination of years of planning, problem-solving and partnership.

"It marks the beginning of an important trial to understand how this technology can help us reduce diesel use, lower associated operational greenhouse gas emissions, and improve efficiency across our rail network," Day said.

Built to withstand extreme heat and rugged terrain, these locomotives feature a seven-megawatt-hour battery system and regenerative braking, which captures energy during downhill runs and feeds it back into the battery.

Day said that the Pilbara has always been a place of big ambition, and the locomotives are a symbol of the kind of innovation required to keep the region going.

The units will be trialled in BHP's iron ore rail routes connecting Pilbara mines to Port Hedland. Image: BHP

That sentiment was echoed by Wabtec regional senior vice president for ANZ and SEA Peter Thomas, who said the battery-electric locomotives' arrival marked a significant milestone for innovation in the region.

"Wabtec is proud to partner with BHP on this important step towards decarbonising rail operations," he said.

"These FLXDrive locomotives are purpose-built to perform in one of the world's most demanding environments, combining advanced battery technology and regenerative braking to deliver high efficiency and lower emissions."

This endeavour to cut emissions and improve productivity has been in the works for some time, with BHP ordering its first four battery-electric locomotives for the WAIO network in 2022, alongside its partnership with Rio Tinto on electric haul trucks in 2024, representing steps to achieve its net-zero goal by 2050.

For BHP's operations, this new initiative is a key piece in its larger decarbonisation puzzle. In 2022, the Big Australian estimated that a full fleet transition to battery-electric locomotives would cut its WA iron ore diesel-related carbon emissions by roughly 30% annually.

Considering the fact BHP leads a fleet of more than 180 locomotives in the Pilbara, this would prove to be a substantial decrease, with this diesel reduction not only slashing carbon emissions but also other pollutants and fuel costs.

Beyond emissions, however, this trial will be an indicator of battery-electric locomotives' operational viability and cost-effectiveness, considering diesel's status is so tied to larger operating expenses.

Powering the Pilbara

BHP is not alone in adopting battery-electric rail.

Rio Tinto purchased its first battery-electric locomotives in 2022, with its managing director of port, rail and core services Richard Cohen highlighting the dual purpose of the technology.

"Battery-electric locomotives offer significant potential for emissions reduction in the near term as we seek to reduce out Scope 1 and 2 carbon emissions in the Pilbara by 50% by 2030," he said at the time.

Hancock Prospecting subsidiary Roy Hill also partnered with Wabtec to introduce the first FLXDrive heavy-haul locomotive in 2023.

Hancock Prospecting group operations chief executive officer Gerhard Veldsman explained the benefits of regenerative braking.

"It will use that stored energy to return to the mine, starting the cycle all over again," he said. "This will not only enable us to realise energy efficiencies but also lower operating costs."

Achieving these companies' goals in the region hinges on the performance and effectiveness of Wabtec's FLXDrive, a component in which the company is very confident, saying it is "designed to replace" diesel locomotives.

Regenerative braking is the key feature within the FLXDrive, especially in the Pilbara, where loaded trains travel downhill to port. That means each locomotive is able to harvest considerable energy per trip.

That stored energy can then be used to power the locomotive when it is heading back to the mine, reducing the need to pull power from the grid or the on-board diesel.

The arrival and trial of battery-electric locomotives in the Pilbara, led by BHP and supported by Rio Tinto and Roy Hill, represents a turning point for heavy-haul rail in Australia.

While challenges no doubt remain around infrastructure and fleet scale, the momentum behind battery-electric locomotives is unmistakable.

These units promise reduced diesel consumption, lower emissions, quieter operation and the potential for reduced maintenance costs. They also demonstrate that resources sectors such as iron ore can lead on innovation while tackling climate challenges.

For the Pilbara, where iron ore rail networks are the arteries of Australia's largest mining operations, battery-electric locomotives represent a future-facing step.

As BHP's trial progresses, the wider mining industry will watch closely, with successful integration potentially opening the door for adoption across other commodities and regions.

BHP's milestone is a signal that Australian mining rail is ready to move into a low-emissions future without compromising performance.

Battery-electric locomotives at a glance:

- **Battery capacity** – seven megawatt-hours
- **Power source** – fully battery-powered, no diesel engine required for trial operations
- **Key feature** – regenerative braking captures energy on downhill runs to recharge batteries
- **Trial route** – BHP's WAIO iron ore network, Pilbara mines to Port Hedland
- **Expected benefits** – lower diesel use, reduced emissions, quieter operation, reduced maintenance costs
- **Fleet context** – BHP operates more than 180 locomotives in the Pilbara; full transition could cut diesel-related emissions by 30% per year

Sigma Lithium's waste piles offer no 'imminent risk,' Brazil mining regulator says

Sigma Lithium's waste piles at a Brazilian mine offer no "imminent risk" and the country's mining regulator saw no need to shut them down during a visit recently.

The ANM's technical staff visited the mine on January 20, about a month and a half after the piles were shut down by labor inspectors who warned of a "grave and imminent risk" to workers and the local community.

The shutdown sent Sigma's shares tumbling some 30% after Reuters reported on the inspectors' decision on January 15.

While ANM's assessment does not overturn the order from Brazil's Labor Ministry, it is a boost for the Toronto-listed miner, as it could be presented as evidence in a lawsuit filed against Brazil's government in early January, in which Sigma seeks to overturn the closure of its waste piles.

The firm announced recently that it was resuming mining activities at its flagship Grota do Cirilo mine in the state of Minas Gerais, and previously said that the shutdown of the piles did not compromise its schedule for resuming production there.

In documents filed to the Labor Ministry, the firm previously said that losing access to the piles would cause "significant operational and economic impacts, in addition to jeopardising the continuity of mining activity."

Sigma declined to comment on the matter due to "ongoing administrative proceedings … in different jurisdictions."

Brazil's largest lithium mine

Sigma's operation at Grota do Cirilo, its only productive asset, is Brazil's largest lithium mine, with annual capacity of 270,000 metric tons of lithium concentrate. It had been inactive since October.

During the visit, ANM's technical staff made a visual on-site assessment of the piles, and analyzed documentation presented by the miner, the agency said.

"ANM technicians did not identify any geotechnical anomalies indicative of an imminent risk of global destabilisation of the piles," it said in a statement.

While the agency found some issues during the visit, it added that it saw no reason for the "adoption of precautionary measures such as closure" of the piles "at the moment."

ANM has notified Sigma that its piles lack a superficial water drainage system, but added that the issue is not "associated with imminent risk" but is a regulatory failure by the firm.

The agency also dismissed what labor inspectors said was a "partial rupture" at one of the waste piles near a school. According to ANM, the issue was a "localised erosion process" on a pile that indicated "local instability" but offered no immediate risk to the local population.

South Africa at pivotal point within its mining industry

Mining built South Africa once. With clarity, confidence, and coherent policy, mining can help to build South Africa's future again – and do so inclusively.

A successful and growing mining industry will expand the economy through the industrial benefits of upstream and downstream multiplier effects on jobs, corporate tax, PAYE, export earnings, VAT collections, as well as enabling the installation of much-required infrastructure.

South Africa must therefore favour market friendly policies and incentives that share risk and reward while reducing unnecessary restrictions that undermine sector competitiveness and investment confidence.

Encouraging signs are emerging such as the Financial Action Task Force removing South Africa from its grey list and S&P Global upgrading the country's credit rating. Lower inflation expectations will temper interest rates, reducing debt costs. Combined, this is signalling progress coming from government and business partnerships to rebuild investor confidence and sentiment.

However, sentiment alone is not investment. Confidence in the South African economy must translate into concrete commitments to infrastructure, mineral development, exploration, research and development, and skills pipelines that future proof the industry, the economy and this country's broader society. Essential to attracting this investment is the pace of critical structural reforms that will encourage and sustain private-sector investment and participation in key areas of the economy.

These are among the many vital points made by Minerals Council South Africa CEO Mzila Mthenjane in a thought-leadership article shortly ahead of Investing in African Mining Indaba in Cape Town from February 9 to 12.

South Africa, Mthenjane emphasises in the article, it is at a pivotal moment in the evolution of its mining industry – "a sector whose historic power and economic influence shaped not just the structure of cities like Johannesburg but the social and economic architecture of South Africa itself".

The legacy of more than a century of mining created cascading employment effects, built infrastructure, generated foreign exchange earnings, and underpinned entire communities.

Yet today, as South Africa approaches its fourth decade of democracy, this country's mining industry faces the dual challenge and opportunity of redefining its place in a modern and technologically driven economy through skilled employees and shaping an inclusive society.

Mthenjane pinpoints the expansion of mining production as the real multiplier of broad based economic impact and social progress that mining brings and not high prices as the central truth that must guide this country's mining strategy.

The mining sector accounted for 5.8% of GDP (nominal) in 2025, a significant source of economic activity but it is lower than 6.2% in 2004, indicating it is simply not realising its full potential, hampered by decades of logistics and energy constraints and inconsistent regulatory changes which have negatively affected investor confidence. Concerted interventions through a public-private partnership model, Operation Vulindlela 2.0, headed by the Presidency, are addressing fundamental bottlenecks, but more and focused efforts are needed to realise the aspired 3% growth rate in the short term.

While commodity price cycles may temporarily boost tax revenue and underpin the mining industry's contribution to the economy, what really drives employment creation and sustainable development of the country is sustained production growth. It is output that stimulates manufacturing and requires an expansion of utilities and general infrastructure and strengthens upstream and downstream supply chains, thus stimulating investment in other industries

For mining to reclaim its catalytic role, all sectors of the value chain must perform effectively and efficiently to amplify these spillover benefits across the economy and kickstart the re-industrialisation of the economy to address unemployment in general and particularly youth unemployment.

This requires an enabling policy environment anchored in security of tenure, long-term stability and predictability to enable business planning and capital allocation. Investors cannot commit large amounts of long term capital if policy volatility threatens value erosion of invested capital and return on investment. Investment houses have a fiduciary duty to generate the expected returns from their investments to provide for all our pensions when we retire from employment.

With the right regulatory reforms, existing mining companies and emerging juniors can become engines of long term economic growth, job creation, and mineral development, particularly in the underexplored or undercapitalised segments of the sector.

Domestic and international economies are transitioning to a low-carbon future with the use of rapidly evolving technologies that rely on the minerals South Africa has in abundance. The definition of what strategically constitutes South Africa's critical minerals underscores the socioeconomic importance of the current mining sector as well as the future supply of minerals that will enable energy and technology transitions. In both instances, exploration is critical to define more mineral deposits.

At the same time, regional cooperation offers untapped potential to use this country's minerals to improve lives and livelihoods through sensible industrialisation policies and

cross-border partnerships that mutually benefit all economies.

Expanding coherent regional cooperation can unlock market opportunities for both consumer and mineral products while stimulating large scale infrastructure investment and attracting long-term global capital that seeks integrated growth horizons. The Southern Africa Power Pool is an available leverage to expand the regional energy mix and enhance energy security and affordability that could expand mineral beneficiation for input into regional development, Mthenjane outlines.

The Southern African region has abundant minerals needed to make the materials to build extensive electricity infrastructure, as well as road, rail and water reticulation systems that will form the foundation of regional industrialisation and growing economies.

Looking ahead, the world has entered a renewed scramble for energy transition minerals, which are critical inputs for technologies ranging from renewable-energy systems to AI hardware.

With its substantial mineral endowments, South Africa has a narrow but once-in-a-lifetime window to position itself as a reliable supplier in this global shift.

Realising this potential requires urgent investment in energy stability, infrastructure rehabilitation, which can be enabled by mining, and serious inroads into reducing crime and corruption to drive social progress that supports a modern mining ecosystem that rests on a globally competitive regulatory environment and transparent mining cadastre.

Crucially, beneficiation should be reframed not as an end in itself, but as a strategic driver of industrial development. Instead of exporting value-added minerals alone, South Africa – as well as the African continent as a whole – can capture greater economic and social value by aligning mineral processing with the massive infrastructure buildouts needed for continental growth.

Finally, policymakers must resist the temptation of short term, restrictive measures – such as ill considered taxes or export bans – that may appear to strengthen the fiscal position but, like Samson pushing against the pillars, risk bringing the entire house down.

With a commodity boom emerging, this is an opportunity to build – not squander – momentum, writes Mthenjane, who concludes with a strong reiteration of mining's inherent ability to serve, once again, as the crucial pillar in the rebuilding of the South African economy for the benefit of every single South African.

US follows Australia with $US12 billion critical minerals reserve

Following Australia's lead, the US Government has launched its own strategic critical minerals reserve, aimed at strengthening domestic supply chain security.

Dubbed Project Vault, the initiative is an independently governed public-private partnership that will store essential raw materials in facilities across the US.

The reserve will be underwritten by a direct $US10 billion loan from the US Export-Import Bank (EXIM), providing long-term financing to a partnership between original equipment manufacturers and private sector capital providers. Around $US1.67 billion had been pledged from private capital sources so far.

"Project Vault is designed to protect domestic manufacturers from supply shocks, support US production and processing of critical raw materials, and strengthen America's critical minerals sector," EXIM chairman John Jovanovic said.

"The US Strategic Critical Minerals Reserve will help manufacturers in the United States compete, grow and lead globally while creating jobs domestically, strengthening our economy and advancing the national interest."

Initial indications of participation from original equipment manufacturers include Clarios, GE Vernova, Western Digital and Boeing, among others. Suppliers servicing Project Vault are expected to include Hartree Partners, Mercuria Americas and Traxys.

Australia launched its own $1.2 billion Strategic Critical Minerals Reserve last year and has committed to implementing the initiative by the end of 2026.

The Project Vault announcement comes as Australia's Federal Resources Minister Madeleine King arrives in Washington for an international summit focused on critical minerals supply chain security.

Australia will join around 20 nations at the United States-hosted meeting, which is expected to examine measures to improve supply chain resilience, including potential pricing mechanisms for certain rare earths and critical minerals.

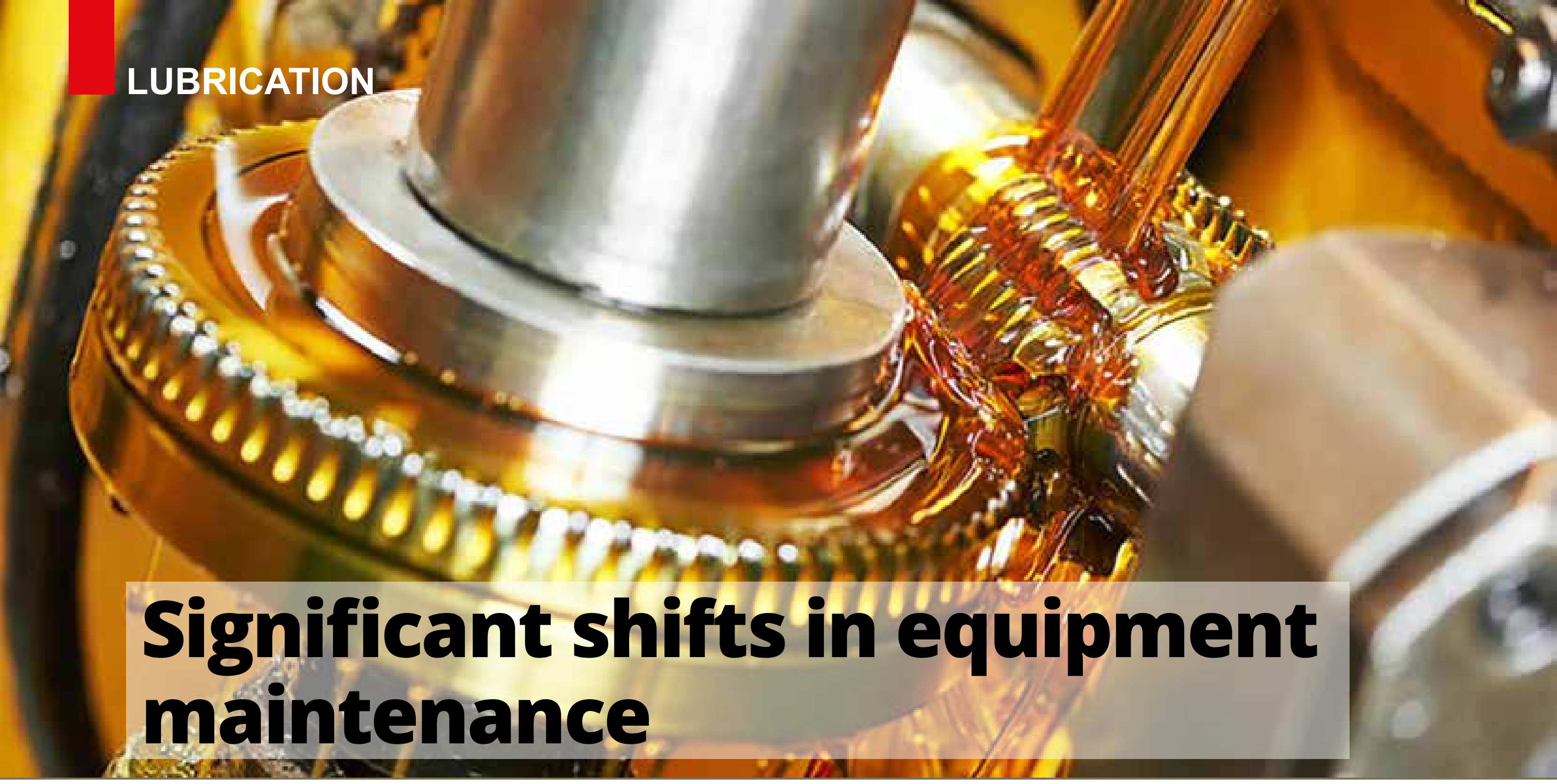
As part of the visit, King will represent Australia at a United States-led Critical Minerals Dialogue of ministers, hosted by US Secretary of State Marco Rubio, and will participate in an industry forum aimed at strengthening cooperation between governments and the private sector.

The meetings support implementation of the Australia–US Critical Minerals and Rare Earths Framework signed by Prime Minister Anthony Albanese and US President Donald Trump in Washington last October.

"Australia has a responsibility to lead on the supply of critical minerals and rare earths globally," King said.

"Australia is at the forefront of global efforts to diversify supply chains for critical minerals and rare earths, which are essential for defence and clean energy technologies."

The summit follows recent G7 discussions on critical minerals and is expected to involve the United Kingdom, United States, Japan, France, Germany, Italy and Canada, alongside countries including India, South Korea, Mexico, Australia, New Zealand and potentially Argentina.



Significant shifts in equipment maintenance

Across the global mining and quarrying landscape, we are witnessing one of the most significant shifts in equipment maintenance philosophy in decades. Lubrication – long regarded as a routine, almost background task – is rapidly becoming a strategic pillar of asset reliability. What was once a manual, schedule-driven activity is now being transformed by digital monitoring, automation, and advanced lubricant formulations designed to withstand the extreme mechanical and environmental stresses of modern mining operations.

The convergence of smart sensors, real-time data analytics, automated delivery systems, and high-performance lubricants is redefining how operators manage wear, friction, and machine health. These technologies are not simply incremental improvements; they represent a fundamental evolution in how the industry approaches reliability engineering. Mines that once relied on periodic inspections and manual greasing are now integrating IoT-enabled condition monitoring, predictive maintenance platforms, and centralised automated lubrication systems capable of delivering precise volumes at optimal intervals. This shift is driven by necessity. As equipment grows larger, production targets rise, and operations push deeper into remote and harsh environments, the cost of unplanned downtime becomes increasingly severe. Modern lubrication technologies offer a pathway to greater uptime, reduced energy consumption, and longer component life – while also supporting the industry's broader goals of safety, sustainability, and operational efficiency.

Gordon Barratt of Mining & Quarry World explores how these innovations are reshaping lubrication practices across the mining and quarrying sectors, and why the integration of digital intelligence into lubrication management is becoming indispensable for the mines of tomorrow.

The mining industry continues to operate under significant pressure to improve profitability, a requirement that depends heavily on the reliability and availability of critical machinery and equipment. In this context, lubrication is not a peripheral consideration but a core engineering function that directly influences asset performance, maintenance costs, and overall operational efficiency.

The technical importance of lubrication within mining operations, the challenges associated with selecting appropriate lubricant systems – including energy-efficient, synthetic, and biodegradable formulations – and the ways in which modern lubrication technologies, supported by digital monitoring and automation, are evolving to meet the sector's demanding conditions. Across the mining value chain, from ultra-class haul trucks to rotary drills and continuous miners, effective lubrication remains one of the most influential yet often under-recognised contributors to equipment reliability.

Mining is fundamental to global resource supply, and the sector's economic performance is tightly linked to equipment uptime. Lubrication plays a decisive role in maintaining mechanical integrity, reducing component wear, and preventing unplanned downtime. Reflecting this importance, the global mining lubricants market was valued at USD 2,255.3 million in 2023 and is projected to grow 4.7% year-on-year in 2024, reaching USD 2,340.5 million. With a forecast CAGR of 5.4% from 2024 to 2034, demand is expected to rise to approximately USD 3,960.2 million by 2034.

Mining operations frequently take place in remote, abrasive, and thermally extreme environments. Equipment used in underground development, surface extraction, and material transport is routinely exposed to high loads, shock events, elevated temperatures, and pervasive dust contamination. Under these conditions, equipment reliability and energy efficiency are critical to sustaining production and maintaining safe working environments. Proper lubrication mitigates wear, reduces failure rates, lowers maintenance expenditure, and enhances operational safety.

Energy consumption presents another major challenge. Global mining activities – across both mineral and rock extraction – account for an estimated 6.2% of total worldwide energy use. Approximately 40% of the energy consumed in mineral mining, equivalent to 46 EJ annually, is expended simply to overcome friction. An additional 2

EJ is required to remanufacture or replace components that fail due to wear. Grinding alone represents 52% of mining's energy demand, followed by haulage (24%), ventilation (9%), and digging (8%).

The economic impact of friction and wear in mineral mining is estimated at 210 billion euros per year. This includes 40% for frictional losses, 27% for replacement parts, 26% for maintenance activities, and 7% for lost production. Adoption of advanced friction-reducing and wear-protection technologies could reduce these losses by 15% over the next decade and by up to 30% over a 20-year horizon. Short-term improvements would yield annual global savings of 31.1 billion euros, reduce energy consumption by 280 TWh, and cut CO_2 emissions by 145 million tonnes. Long-term improvements could double these benefits.

One of the most effective pathways to reducing friction and wear is the deployment of high-performance lubrication solutions, including energy-efficient lubricants and advanced synthetic or specialty formulations. These solutions complement parallel advances in metallurgy, surface engineering, protective coatings, and component design across gearboxes, engines, shovels, shields, crushers, seals, bearings, conveyors, pumps, fans, hoppers, and feeders. Each subsystem presents unique tribological challenges, and incremental improvements across these areas collectively reduce wear, extend component life, and lower maintenance costs – an important consideration given that maintenance represents a substantial portion of total mining operating expenditure.

Lubrication has long been a critical engineering challenge in mining due to the heavy-duty nature of the equipment involved. Draglines, hydraulic excavators, electric rope shovels, haul trucks, loaders, drilling rigs, and processing machinery all rely on robust lubrication strategies to maintain performance under severe operating conditions.

Mining operations depend on a diverse fleet of equipment across exploration, extraction, haulage, processing, and reclamation. The following sections outline the primary categories of machinery used in the industry and the lubrication requirements associated with each.

Exploration and drilling activities rely on a range of specialised equipment. Core drilling rigs are deployed to obtain subsurface geological samples, while rotary drills are essential for creating large-diameter holes in hard rock formations. Percussion drills are commonly used for drilling blast holes, and sonic drills support geotechnical investigations and environmental assessments. Mud pumps circulate drilling fluids throughout the drilling process, and blast-hole drills prepare the ground for blasting operations. As the mining sector has long demonstrated, lubrication remains a persistent engineering challenge across these systems, as proper lubrication is fundamental not only to performance but also to the reliability and efficiency of drilling machinery.

Excavation operations depend on machines designed to move large volumes of earth and rock. Excavators perform the bulk of digging and material removal, complemented by backhoes for smaller-scale excavation, lifting, and handling tasks. Front-end loaders transport and load bulk materials, while large electric or diesel-powered shovels handle heavy digging and scooping duties. Draglines remove overburden in surface mines, and bucket-wheel excavators provide continuous excavation capability in large open-pit operations.

Crushing and screening processes utilise several types of equipment. Jaw crushers perform primary reduction of large rock, followed by cone crushers for secondary and tertiary size reduction. Impact crushers handle softer materials requiring less force, while gyratory crushers support large-scale ore processing. Roll crushers are used for softer to medium-hard minerals. Vibrating screens classify crushed material by size, and grizzly feeders separate coarse material from finer fractions.

Material transport within mines is supported by conveying systems. Conveyor belts move mined material efficiently across distances, bucket elevators lift material vertically, and radial stackers build stockpiles in controlled formations. Additional material handling relies on forklifts for short-distance transport, cranes for lifting heavy equipment, and hoists for vertical load movement.

Blasting operations require a suite of specialised tools. Explosives break rock, blasting machines ensure safe detonation, and detonators initiate explosions within blast holes. Blast mats control fly rock, while trained shotfirers oversee the entire blasting process. Drilling and blasting systems also include down-the-hole drills for penetrating hard rock and hydraulic drills commonly used in blast-hole drilling in hard-rock mines.

Haulage and transportation systems form the backbone of material movement. Dump trucks transport large volumes of material, articulated haulers operate effectively on rough terrain, and loaders transfer material into haulage units. Haul trucks carry ore and overburden, rail haulage systems support long-distance movement in certain operations, and tippers handle loose materials efficiently.

Processing plants rely on equipment designed to liberate, separate, and refine minerals. Ball mills grind ore into fine powder, while rod mills reduce material to smaller sizes. Flotation cells separate minerals based on surface chemistry, and thickeners remove water from slurry streams. Leaching equipment extracts metals using chemical solutions, gravity separators classify material by density, and magnetic separators isolate magnetic minerals. Hydro-cyclones perform classification and separation, and shaking tables further refine material based on density and particle size.

Ventilation systems are essential for underground operations. Ventilation fans circulate fresh air and remove harmful gases, air scrubbers clean dust-laden or contaminated air, and integrated underground ventilation networks maintain safe airflow throughout mine workings.

Pumping systems manage water and slurry movement. Water pumps support dewatering, slurry pumps handle mixtures of water and ore, sump pumps remove accumulated water from shafts, and pneumatic pumps serve various fluid-handling applications.

Mining support and auxiliary systems enhance safety and structural stability. Bolting machines secure mine roofs, roof support systems prevent collapses, and ground support systems stabilise excavated areas. Exploration samplers collect geological samples, grout plants inject stabilising grout into tunnels, and underground mining carts transport ore and waste through confined spaces.

Underground mining relies on specialised machinery. Continuous miners cut rock and ore continuously, longwall miners extract material from extensive horizontal panels, and room-and-pillar equipment supports operations in mines using this layout. Load-haul-dump (LHD) machines perform loading, hauling, and dumping tasks in confined underground environments.

Safety and health systems are integral to mining operations. Gas detectors monitor air quality, personal protective equipment safeguards workers, and escape chambers provide refuge during emergencies. Fire suppression systems protect vehicles and equipment, first aid kits support medical response, and CCTV systems enhance operational monitoring and safety oversight.

Waste management infrastructure includes tailings dams for storing processing by-products, sludge tanks for handling waste streams, and equipment dedicated to managing waste rock removed during mining.

Reclamation and rehabilitation activities employ dozers to reshape landforms, compactors to stabilise soil, hydro-seeders to establish vegetation, and topsoil spreaders to restore soil layers across reclaimed areas.

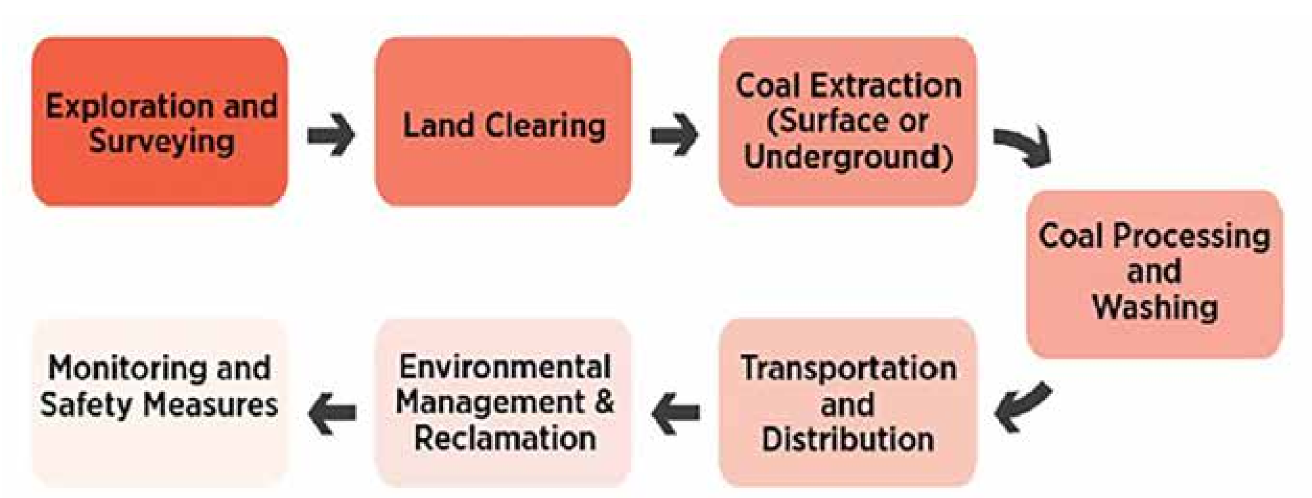


Figure 1: Process chart for coal mining

Table 4: Lubricant types, additive concentrations and typical applications

Application Type	Typical Additive Type	Additive % Used in Oil
Circulation Oil (Turbine, Compressor)	**R&O Classification -** Antioxidants, Corrosion inhibitors, Defoamant, Demulsifier	0.5 to 5%
Hydraulic Oil (Non FR Hydraulic)	**AW Classification -** Antiwear Agents Antioxidants, Defoamant, Demulsifier, Corrosion Inhibitors, Pour Point & VI Improvers	2.0 to 5.0%
Gear Oils (Automotive and Industrial Torque Reducer / increaser, Geared Drive)	**EP Classification -** Antiwear Agents Antiseizure Agents, Antioxidants, Defoamant, Demulsifier, Corrosion Inhibitors, Pour Point and VI Improvers	2.0 to 10.0%
Engine Oils (Gasoline, Diesel, Natural Gas)	**PCMO/DEO Classification -** Antiwear Agents, Antioxidants, Defoamant, Corrosion Inhibitors, Dispersants, Alkaline Reserve, Pour Point & VI Improvers	10.0 to 30.0%

Effective lubrication sits at the core of reliable mining operations. It is the mechanism that reduces friction, limits wear and protects critical machine components from premature failure. In an industry where equipment is routinely exposed to extreme temperatures, high pressures, heavy mechanical loads, and pervasive dust contamination, maintaining proper lubrication is essential for minimising downtime, sustaining performance, and extending asset life – particularly in remote mining locations where maintenance access is limited.

Achieving optimal performance requires far more than simply applying a generic lubricant. Lubrication strategies in mining must be engineered to match the specific operating conditions of each machine. This demands careful consideration of viscosity behaviour, load-carrying capability, thermal stability, resistance to oxidation, and the ability to control contamination. Understanding these parameters is fundamental to maximising equipment efficiency, reliability, and safety. The combination of heavy loads, elevated temperatures, and abrasive environments means that only high-performance, purpose-designed lubricants can deliver the durability and operational effectiveness required in modern mining systems.

Selecting the correct lubricant is only part of the challenge. Application techniques must also be appropriate for the equipment and its operating environment. Many lubrication points on large machines – such as draglines, shovels, and large excavators – are difficult to access, making consistent and timely lubrication difficult. In addition, formulations must increasingly meet human-health and environmental expectations. Lubricant developers are therefore under pressure to eliminate carcinogenic or toxic components while still delivering the performance demanded by mining equipment. As a result, environmentally responsible formulations are becoming more common, balancing operational requirements with reduced ecological impact.

The challenges associated with lubrication in mining are extensive. Mining environments, whether in coal, iron ore, or other commodities, are heavily contaminated with dust and particulates that rapidly degrade lubricants. Equipment is subjected to extreme mechanical loads, requiring lubricants and greases with high load-bearing capacity and strong resistance to welding or scuffing under severe pressure. Moisture is another persistent threat, as water ingress accelerates lubricant degradation and promotes corrosion. Temperature fluctuations – ranging from sub-zero conditions to high thermal loads – further complicate lubricant performance, demanding formulations capable of maintaining stability across wide temperature ranges.

Monitoring and conditioning lubricants is also difficult due to the remote and dispersed nature of many mining operations. Large fleets of draglines, shovels, excavators, dump trucks, and support equipment often operate across vast areas, making regular inspection and maintenance logistically challenging. For example, operations such as those managed by BCCL in India span dozens of underground, open-cast, and mixed mines, along with multiple washeries, illustrating the complexity of maintaining consistent lubrication practices across geographically distributed assets. Administrative challenges arise as well, since centralised control of lubrication programs becomes difficult when equipment is spread across remote regions with limited accessibility.

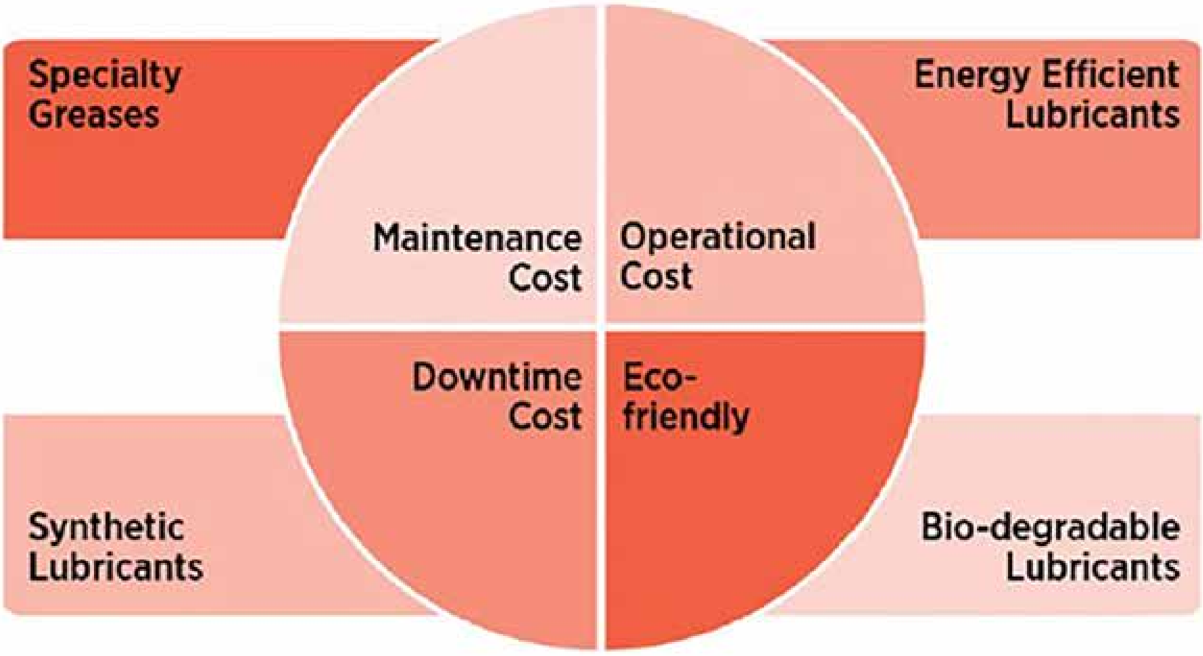


Figure 2: Types of lubrication with their purpose

Health and environmental considerations add another layer of complexity. Modern mining operations place significant emphasis on reducing worker exposure to hazardous substances and minimising environmental impact. Lubricant suppliers must therefore develop formulations that avoid harmful additives while still providing the necessary protection against friction, wear, and thermal degradation. Eco-friendly lubricants are increasingly important as the industry seeks to balance operational performance with sustainability goals.

As mining operations grow more demanding, lubricant manufacturers face increasing pressure to deliver solutions that not only meet OEM performance specifications but also help reduce maintenance costs, extend component life, and support broader health, safety, and environmental objectives. The development of advanced lubrication technologies is therefore becoming a critical enabler of reliability and efficiency across the mining sector.

Mineral-oil-based lubricants continue to dominate mining applications because they are widely available, cost-effective, and suitable for high-volume use in hydraulic systems, engines, and gearboxes across heavy-duty equipment such as excavators, dump trucks, backhoe loaders, draglines, and drilling rigs. The mining sector remains highly price-sensitive, which slows the transition to more advanced formulations. However, the shift toward specialty and synthetic lubricants has already begun as tribological challenges become more apparent and engineers increasingly recognise the performance limitations of conventional mineral oils.

Greases remain essential across many mining machines, including dump trucks, excavators, crushers, and draglines. These components operate under severe mechanical loads, making high load-carrying capacity a critical requirement. Greases must withstand high Timken and weld loads, resist impact loading, and maintain structural integrity under shock conditions – characteristics that standard greases cannot reliably provide. Moisture and dust contamination further complicate lubrication, necessitating greases with strong water resistance, dust resistance, and robust tackifier and additive systems to protect bearings, pins, bushings, and other exposed components.

Certain applications demand high-temperature greases, typically based on bentonite or clay thickeners, which offer high drop points or non-dropping behaviour to ensure stability in thermally extreme environments. In areas where lubricated components are exposed to chemicals – such as bearings, shafts, and axles – chemical-resistant greases are required to maintain film strength and prevent degradation.

Energy-efficient lubricants have become increasingly important as mining operations pursue higher productivity, lower operating costs, and reduced environmental impact. These lubricants minimise friction more effectively than conventional formulations, improving mechanical efficiency in equipment such as drills, haul trucks, and crushers. Reduced friction translates directly into lower fuel consumption and measurable energy savings. Modern energy-efficient lubricants are often synthetic or semi-synthetic and incorporate advanced additive technologies, including nanomaterials designed to enhance boundary and mixed-regime lubrication where metal-to-metal contact is most likely.

The growing emphasis on sustainability places additional pressure on formulators to develop biodegradable oils and greases capable of withstanding the severe operating conditions typical of mining. Synthetic lubricants, particularly those based on API Group IV (PAO) and Group V (esters), are increasingly adopted because they offer superior performance under extreme temperatures, pressures, loads, and moisture exposure. Although more expensive, synthetic lubricants provide significantly longer service intervals than mineral oils, reducing both lubricant consumption and waste generation. Their extended life cycles contribute indirectly to environmental stewardship by lowering the volume of used oil requiring disposal.

Biodegradable lubricants are gaining support from both mining companies and regulatory bodies seeking to

reduce environmental impact. Esters from API Group V are especially suitable because they are inherently biodegradable while still delivering high performance under demanding conditions. Developing biodegradable lubricants that can endure the mechanical and thermal stresses of mining remains a significant engineering challenge, but progress continues as sustainability becomes a core operational priority.

Selecting and applying the correct lubricant has a direct influence on maintenance costs, equipment uptime, and overall profitability. Proper lubrication reduces wear, prevents premature component failure, and minimises unplanned downtime. In parallel, the adoption of advanced lubrication practices – such as automated lubrication systems, condition monitoring, and data-driven maintenance strategies – further enhances equipment reliability and reduces operating costs. Together, high-performance lubricants and modern lubrication management practices form a critical foundation for improving the efficiency, durability, and sustainability of mining operations.

Best practices for lubrication in the mining sector increasingly revolve around monitoring, precision, and data-driven maintenance. Lubrication monitoring and condition-based maintenance have become central to reliability engineering, with oil analysis serving as one of the most effective tools for detecting contamination, degradation, and wear metals. Regular analysis of used oils provides early insight into component health, enabling proactive interventions that preserve lubricant integrity and extend equipment life. Alongside laboratory analysis, condition-monitoring systems equipped with IoT-based sensors now provide real-time data on lubricant condition, temperature, viscosity changes, and contamination levels. These systems allow engineers to predict potential failures before they occur, reducing unplanned downtime and significantly improving system reliability across mining operations.

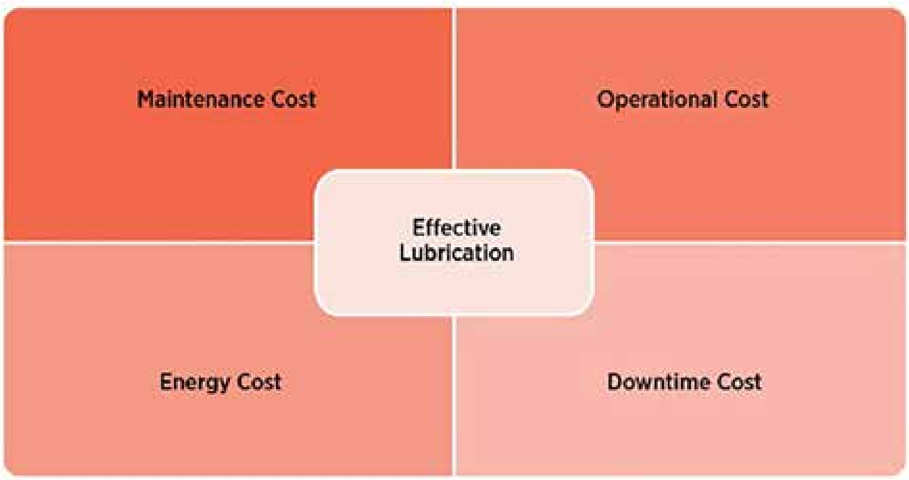


Figure 3: Swing from effective lubrication

Automated lubrication systems further enhance reliability by ensuring that critical components receive the correct amount of lubricant at the right intervals without relying on manual intervention. Centralised lubrication systems are now common on crushers, conveyors, and other high-duty equipment, where consistent lubrication is essential for maintaining uptime and reducing wear. These systems minimise human error, improve lubrication accuracy, and reduce maintenance labour requirements.

Proper storage and handling of lubricants remain equally important. Contamination introduced during

storage, transfer, or handling can compromise lubricant performance long before it reaches the equipment. Mining operations must therefore maintain strict adherence to manufacturer guidelines for storage conditions, filtration, and dispensing practices to ensure that lubricants retain their designed properties.

Training is another critical component of effective lubrication management. Many lubricant suppliers conduct technical workshops and seminars for frontline managers, supervisors, and operators to ensure that personnel understand lubrication fundamentals, application techniques, and the consequences of improper practices. Ongoing training programs have a measurable impact on equipment longevity and operational reliability, particularly in large mining operations where staff turnover and varying skill levels can affect maintenance consistency.

Digitalisation and the integration of IoT technologies have transformed lubrication practices across the industrial sector, and mining is no exception. As equipment operates under extreme loads, temperatures, and environmental stressors, the need for precise and reliable lubrication becomes even more pronounced. Traditional lubrication methods often suffer from inefficiencies, inconsistent application, and a lack of real-time visibility. Digital tools now address these limitations by enabling continuous monitoring, automated alerts, and predictive maintenance strategies.

IoT devices embedded in mining equipment monitor lubrication levels, contamination, and operating conditions, allowing maintenance teams to predict lubrication needs before failures occur. This shift from reactive to predictive maintenance reduces breakdowns and extends component life. Data analytics further enhances lubrication management by enabling mining companies to optimise lubricant consumption, improve operational efficiency, and reduce overall maintenance costs. Machine learning and artificial intelligence are beginning to play a role as well, analysing large datasets to determine optimal lubrication intervals and predict when replenishment or replacement is required. Although widespread adoption in mining is still developing – largely due to the remote and dispersed nature of mining operations – these technologies represent the future of lubrication management.

In the mining industry, where operational efficiency and equipment reliability are essential, lubrication solutions directly influence productivity, safety, and maintenance expenditure. Continuous research and innovation are required to meet the increasing demands of modern mining while addressing environmental and operational challenges. The industry must continue to embrace digitalisation and advanced lubricant technologies, including energy-efficient formulations, which reduce frictional losses, lower energy consumption, and improve system reliability.

Extreme operating conditions, abrasive environments, and the growing emphasis on sustainability demand lubrication strategies that are both robust and adaptable. Automated lubrication systems, IoT-enabled sensors, and predictive analytics provide significant advantages by enabling precise application, real-time monitoring, and informed decision-making. These innovations enhance the overall effectiveness of lubrication practices and support the long-term reliability of mining equipment.

Looking ahead, the future of lubrication in mining will be shaped by continued advancements in digitalisation, predictive maintenance, and environmentally responsible formulations. As mining companies adopt these technologies, they will be better positioned to meet evolving operational demands while improving both efficiency and environmental performance. Ultimately, investing in the right lubrication solutions is not merely a maintenance decision – it is a strategic investment in the long-term resilience and success of the mining industry.

Designing tailings solutions based on operational realities

The trend towards greater throughputs at concentrators means that the quantity of tailings being produced is increasing. Operators can build bigger pipelines and pumping stations to manage this, but, in many instances, this will only exacerbate existing logistical challenges and oversight requirements.

Tailings dams are rising, which means operators need to make decisions regarding what to do about their diminishing capacity. Depending on the site, there will inevitably be constraints within which these decisions have to be made (i.e. regulatory requirements, space constraints, etc).

These decisions also inevitably involve challenges around oversight; for instance, there are important geotechnical and environmental considerations that must be taken into account.

It is possible, in theory, to go on building larger pumping systems, but, at some point, this becomes unmanageable and uneconomic. There is a ceiling on the economies of scale, and, in some operations, it might be more efficient to have two smaller pumping systems, rather than one big pumping system.

DESIGNING SYSTEMS ACCORDING TO OPERATIONAL SCENARIOS

If there is just a single pumping system and there are reliability issues that require the system to be shutdown, then production stops. But if an operation has multiple smaller systems and there are reliability issues with one system – or even when scheduled maintenance needs to be performed – it is still going to have some pumping capacity, albeit reduced, which means there will be less downtime.

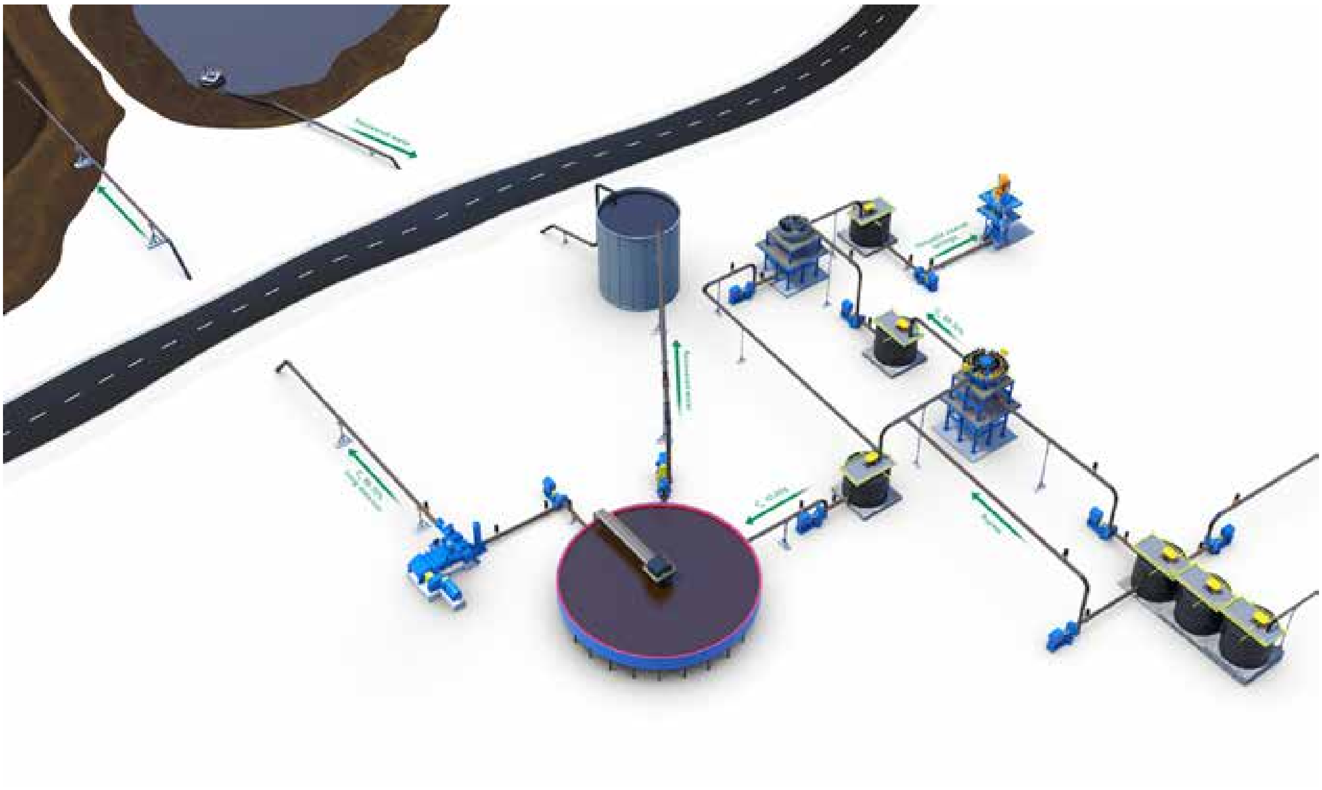
This then provides operators with greater flexibility. For instance, if a system is sized for one big flow and the pipeline needs to operate at between, say, 70-100% capacity to maintain velocity, it is not difficult to envisage a situation in which it might have to run its thickeners empty. This is obviously inefficient and energy intensive.

When designing these systems, it is crucial that the operational scenarios guide the design decisions.

FLOWSHEET-BASED APPROACH

Weir is developing tailings flowsheets. This means that it is taking a more holistic approach; rather than focusing solely on managing the flow as one big volume, it is looking at separating out the different size fractions, which then allows operators to manage them in different ways. This is about designing systems that provide greater operational flexibility.

The operator can apply cycloning or screening technology to dewater the tailings, which can remove the coarser fractions. This has benefits in terms of reducing the load on the thickener, while also allowing them to reduce the size of their pipeline.



Weir's TerraflowingTM dewatering technology provides optimal balance between energy consumption and water recovery.

Another solution that some miners are thinking about and starting to implement is using coarse particle flotation (CPF) technology to increase their throughput. If there is an existing Semi-Autogenous Ball Mill Crusher (SABC) circuit, introducing CPF reduces the load on the comminution circuit because it reduces the amount of material that needs to be finely ground.

This allows operators to run the plant at the same or improved (if it can capture valuable metals that might have been lost in conventional flotation at coarse grind size) recovery, but at a higher throughput, while also producing a coarser tailings stream.

The coarse tailings produced by CPF are particularly valuable for tailings storage facility (TSF) construction. Free-draining sands – defined by a fines content of less than 15–18% passing seventy-five µm – can be used to build stable embankments and reduce water retention. Hydrocyclones are commonly used to separate these sands from finer material.

This approach aligns with modern tailings strategies that emphasise safety, sustainability, and a reduced footprint.

ASSESSING PROJECT FEASIBILITY

When designing and developing any solution there are always going to be trade-offs that need to be considered and that is no different for CPF.

It does represent significant capital investment, and, in brownfield projects, it must fit within the existing footprint. So, these things always need to be assessed on a case-by-case basis.

CPF also requires additional water, which can be recovered, but that needs to be investigated during the feasibility stage. Similarly, there are additional energy requirements, so all these factors – and more – need to be weighed against the increased throughput.

However, that said, while these projects must be evaluated individually, CPF generally provides operational benefits and is likely to see broader implementation in the future.

Weir collaborates with its customers, consultants and EPCs to encourage them to adopt new technologies. While innovation is a popular topic of discussion these days, mining remains a risk-averse sector, so it is important that OEMs like Weir are working hard to encourage adoption by validating more innovative technologies and solutions and demonstrating that they can deliver quantifiable benefits.

DRIVING INNOVATIVE, SUSTAINABLE SOLUTIONS

Weir engages in some very exciting projects that have the potential to make some significant progress in reducing tailings' environmental burden.

For instance, in South America, Weir is working on various studies with partners to investigate how to get a fines-free product that is suitable for alternative TSF disposal scenarios.

In Australia, it is doing test work with its TerraflowingTM dewatering technology to explore alternative approaches to thickening as a way of recovering more water. It is an approach that Weir thinks might provide more flexible flowsheets, particularly for those operating in arid regions.

TRANSFORMING TAILINGS PIPELINES

Weir is also now offering operators pipeline solutions that have proven particularly well-suited to tailings applications,

Formed flanges and face-to-face sealing of Arterra™ UHMWPE pipelines ensure smoother connections, reducing turbulence and wear.

where long distances and abrasive slurries create the most demanding conditions.

Weir's advanced pipeline solution Arterra™ is an ultra-high molecular weight polyethylene (UHMWPE) material proven in medical implants and marine applications. It is extending pipeline life significantly in some of Australia's harshest environments.

The key to the performance of Arterra™ UHMWPE pipelines lies in the molecular structure of UHMWPE itself. Arterra™ pipes have a molecular weight of 3.5×106 grams per mole (g/mol), compared to HDPE with a molecular weight of 0.5x106g/mol. With a surface roughness of just 0.2 microns, the material is exceptionally smooth, almost hydrophobic in its resistance to adhesion.

The surface smoothness of this material offers friction benefits that translate directly to reduced power requirements and extended service life, resulting in significant yearly savings at sites that have made the switch.

For instance, a South Australian iron ore operation was using conventional high-density polyethylene (HDPE) pipelines, which were wearing through in 3–4 weeks.

It had some slack flow portions of the pipeline. Because of the steep slope, the material was moving faster than it was being pumped – 12m per second, which is incredibly fast for pipeline operations.

When particles are pushed at that velocity through a pipe filled with high-density solids, the wear is relentless.

The site's initial response – replacing failed sections every 4–6 weeks – was costly and operationally disruptive. After switching to Arterra™ UHMWPE pipeline, the same sections now last 16–18 months – that is a 16-fold improvement in service life.

Building a more resilient mining industry

Weir is not just responding to changes in the mining industry – it is actively shaping them. Through its commitment to innovative engineering, Weir is enabling a new era of sustainable and efficient mineral processing and tailings management.

By investing in research and development, Weir is helping mining operations around the world reduce energy use, improve tailings management, and extend the life of critical infrastructure.

AUTHOR
Erik Vlot
Weir, Global Tailings Process Director

What sustainability means in a mining context

Mining remains fundamental to modern society, supplying the critical minerals and metals that underpin infrastructure development, manufacturing, and advanced technologies. At the same time, the inherently extractive nature of the industry can create significant environmental and social challenges if not managed effectively. As expectations from regulators, investors, and communities continue to rise, mining companies are placing greater emphasis on sustainable operating models that reduce impacts and support long-term project viability.

In mining, sustainability refers to the integrated management of environmental performance, social responsibility, and economic value throughout the life of an operation. It encompasses:

- Efficient resource extraction that maximises ore recovery while minimising waste generation and energy consumption.
- Responsible sourcing and supply-chain transparency, ensuring materials are produced in line with global ESG standards.
- Protection of biodiversity and ecosystems, including land stewardship, water management, and progressive rehabilitation.
- Safe, healthy, and equitable working conditions for employees and contractors.
- Constructive engagement with host communities, ensuring that mining contributes to local development and minimises adverse impacts.

Stakeholders across the sector – regulators, NGOs, investors, and community groups – are increasingly demanding stronger sustainability performance. Concerns range from mining's contribution to greenhouse-gas emissions and long-term resource depletion to the safety and well-being of workers and nearby residents. As a result, implementing robust sustainable mining practices is no longer optional; it is essential for maintaining social licence, reducing operational risk, and ensuring the longevity of mining operations.

CHALLENGES TO SUSTAINABILITY IN MINING

A major constraint on sustainable mining is the accelerating global demand for minerals. Population growth, electrification, and the expansion of low-carbon technologies are driving unprecedented consumption of metals. Meeting this demand while maintaining environmental performance and social licence requires new extraction methods, improved process efficiency, and smarter resource management.

Resource depletion adds another layer of complexity. Many high-grade deposits are already exhausted or in decline, pushing operations toward lower-grade ores, deeper deposits, and more complex geologies. This shift increases energy intensity, water use, waste volumes, and overall operating costs. Without long-term planning and responsible resource stewardship, depletion can trigger supply instability, economic disruption, and additional environmental pressure.

Environmental impacts remain a central challenge. Mining can alter landscapes, disturb ecosystems, and generate air and water pollution if not properly controlled. Tailings storage, acid rock drainage, dust emissions, and water consumption are particularly scrutinised. In many regions, mining competes with agriculture, communities, and industry for limited water resources, making water efficiency and recycling essential.

IMPROVING SUSTAINABILITY IN MINING

Mining companies can strengthen sustainability performance through a range of operational and strategic measures.

RESPONSIBLE SOURCING

Responsible sourcing frameworks help ensure that extracted materials are not linked to environmental harm or human rights violations. This includes:

- Rigorous supply-chain due diligence
- Verification of contractor and supplier compliance
- Alignment with international ESG standards and reporting frameworks

These practices support transparency and reduce reputational and regulatory risk.

Improving resource efficiency is central to sustainable mining. Key approaches include:

- Optimising mine planning to maximise ore recovery and reduce dilution
- Deploying energy-efficient equipment and electrified fleets
- Enhancing water recycling and reducing freshwater intake
- Implementing advanced process control to improve throughput and reduce reagent use
- Reducing waste generation through better ore sorting, pre-concentration, and tailings reprocessing

These strategies lower operating costs while reducing environmental footprint.

Optimising the use of natural resources and reducing waste is central to sustainable mining. Improving ore recovery, minimising dilution, enhancing process efficiency, and reducing energy and water consumption all contribute to lower operating costs and a smaller environmental footprint.

Mining activities can significantly alter local ecosystems. Engineers can help mitigate these impacts by supporting detailed baseline biodiversity assessments, integrating avoidance and minimisation measures into mine design, and planning progressive rehabilitation and post-closure landform stability. Effective water management, erosion control, and habitat restoration are key components of this work.

Worker safety remains a core pillar of sustainable operations. Maintaining safe working conditions requires robust training programs, proper equipment selection, effective ventilation and ground-control systems, and continuous monitoring of occupational hazards. A strong safety culture reduces incidents and supports long-term workforce well-being.

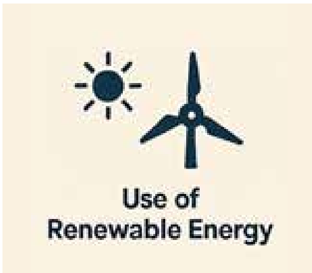
Sustainable mining also depends on constructive engagement with host communities, regulators, and NGOs. Transparent communication helps build trust, identify potential impacts early, and develop mitigation strategies that align with community expectations and regulatory requirements. This engagement is essential for maintaining social licence to operate.

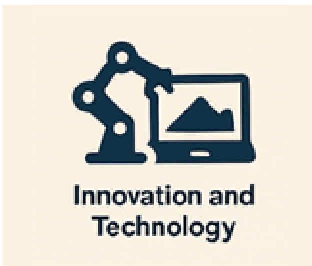
Integrating renewable energy sources – such as solar, wind, or hybrid microgrids – can reduce greenhouse-gas emissions and lower long-term energy costs. For remote operations, renewables can also improve energy security and reduce reliance on diesel generation.

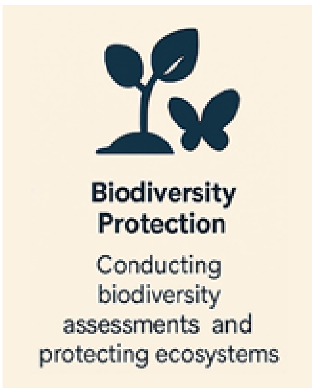
Advances in technology offer powerful tools for improving sustainability performance. Artificial intelligence, automation, drones, and sensor networks can enhance orebody knowledge, optimise haulage and processing, reduce waste, and improve predictive maintenance. These technologies also strengthen safety by reducing worker exposure to hazardous environments.

CONCLUSION

Sustainable mining practices are essential for the long-term viability of the industry, the protection of the environment, and the well-being of workers and communities. Although the challenges are substantial, mining companies are increasingly adopting integrated sustainability strategies that involve engineering innovation, operational efficiency, and active stakeholder participation. By embedding these practices across the mine life cycle, the industry can reduce its environmental and social impacts while positioning itself for long-term success.







Misaligning with safety & production targets

Shifting material causing mistacking

When a bulk-handling conveyor belt drifts out of alignment, one side moves higher than the other. This causes the load to shift off-center, emitting dust and dropping spillage as the situation worsens the farther the belt travels. That is the point when safety degrades and costs skyrocket.

If there is a stop mechanism, it will grind everything to a halt and lead to unscheduled downtime, over and over again, until the misalignment is resolved. Without a stop mechanism, material can spill along the belt path, idlers and pulleys will get fouled, and the belt can rub against the stringer, causing belt damage and a potential friction fire. However, there are safe and easily retrofitted technologies that ensure the stop mechanism is rarely (if ever) needed.

This article will explain some of the main causes of belt misalignment and offers practical solutions to ensure the conveyor belt remains centered throughout the entire rotation.

WHAT CAUSES BELT DRIFT?

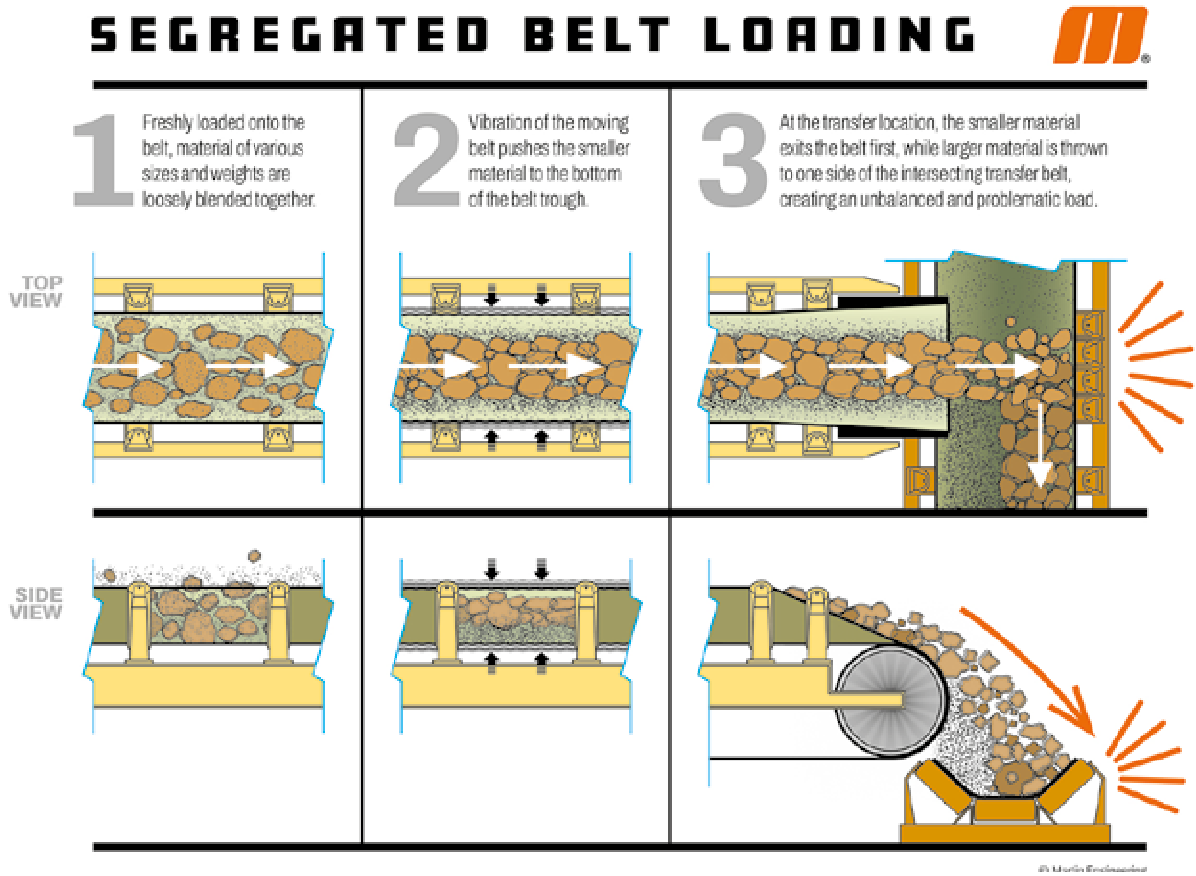
A belt can either suddenly slip out of alignment or gradually drift off center over time. Two main conditions that cause this are operating conditions and equipment conditions. Operating conditions include environmental or application factors, such as high winds or segregated loading. Equipment conditions encompass components from idlers to the belt itself. The quality of the equipment and its ability to adapt to changes in production, like faster belt speeds and higher volumes, also play a role.

OPERATING CONDITIONS

- *Segregated Loading* – Particularly in applications like quarrying, mining, and construction and demolition (C & D) material recycling, fines can separate from larger materials and settle on the bottom of the conveyor. When transferred to a perpendicular (90º) transfer belt, larger material will settle on the far end of the belt, causing it to drift.

- *Support* – Conveyors can experience regular misalignment when installed on uneven ground, soft ground, or between towers where settling can affect alignment.

- *Wind* – High velocity prevailing winds may necessitate a cover over the conveyor or pointed in the direction of common wind patterns.



The behavior of the material is something that operators and design engineers need to take into account for safety.

- *Temperature* – Extreme temperatures on one side of the conveyor can cause components to expand, leading to changes in friction and belt contact. This uneven exposure also occurs with large amounts of snow, rain, or frost, and if it persists, it might require a cover or enclosure.

- *Structure* – The structure of the system may cause misalignment due to settling into the ground or weakening over time due to constant weight and vibration. The balance and calibration should be checked periodically at multiple points along the conveyor structure.

- *Outside force* – If bumped by machinery or affected by seismic activity, it should be tested for levelling immediately. Realignment of the structure or support may be required.

EQUIPMENT CONDITIONS

- Idlers and Pulleys – All rolling components steer the belt. To ensure proper alignment, rolling components must be:

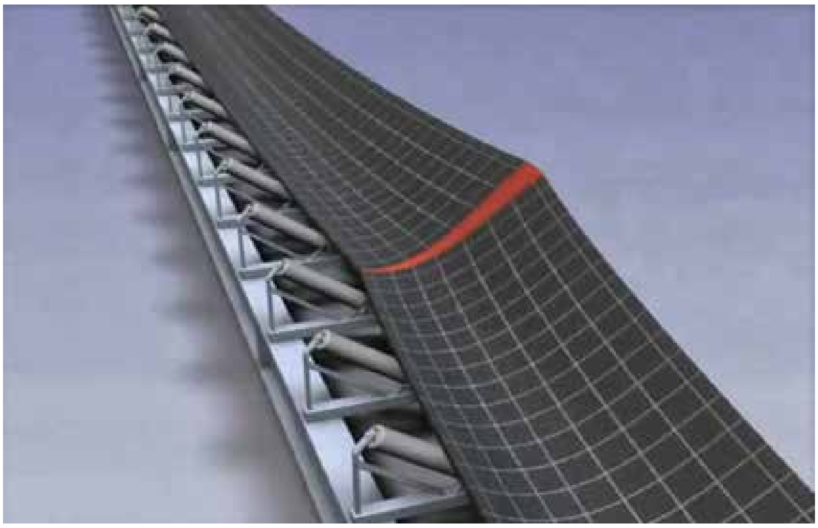
  - *Clean* – A fouled pulley face can cause slippage, leading to belt rippling, excessive friction, and higher power consumption. A fouled roller face may be too slick to roll.

  - *Rolling* – Dust and spillage can gum up roller bearings and pulley machine parts, causing them to freeze. This can lead to increased friction, which degrades the belt and raises the risk of a belt fire.

  - Aligned – A single idler that is slightly out of alignment can trigger drift down the belt path. Using a mallet to adjust idler supports for belt alignment is ill-advised, as it can completely throw off calibration for a new belt installation.

  - Touching the Belt – The belt must touch all pulleys and idlers evenly to be effectively aligned.

A seized idler wears down from belt friction, creating a potential fire hazard.



Mistracking can put strain on the splice which can result in safety issues.

- Uncentered Loading – The material's center of gravity will seek the lowest trough point. If the material is not loading centered, such as a dead drop down a transfer chute allowing splashing and shifting, the uneven weight distribution will cause the belt to drift. In this event, a scoop or spoon-shaped loading chute that slows material and distributes it at the center of the belt is recommended.

- Belt and Splice – If the belt is poorly manufactured or stored improperly, it can bow or camber. Poor installation of a vulcanized or mechanical splice can result in a splice that causes belt tracking problems.

PROBLEMS AND INDICATORS OF MISTRACKING

When the belt mistracks, the indicators will be apparent, especially if the system is equipped with a stop mechanism. The main reason for a stop mechanism is the moving belt's contact with a static frame. Aside from the expensive belt edge damage, the friction can break the splice or ignite combustible dust or cargo, potentially causing a fire or explosion.

As one side of the belt rises higher, material spills along the belt path. Cleanup requires shutting down the system so workers can do it safely. This can raise labor costs, but operators often perform this task while the belt is still running, which can lead to injuries or fatalities. Alternatively, front loaders or industrial vacuums can be used for cleanup. Only trained staff should operate this equipment because contact with the conveyor structure can throw the system out of balance and cause mistracking issues.

Vertical edge guides act as more of an indicator of mistracking and can create more issues due to severe belt drift.

Like belt friction on the mainframe, frozen idlers from fouled roller faces and bearings due to spillage can carry the same potential for a belt fire. Instead of shredding the belt edge, it degrades the less-protected bottom side of the belt. Damage to one side of the belt produces the formula for mistracking. Replacing a single idler can require unscheduled downtime, as well as equipment and labor costs.

DO STANDARD OEM CONVEYOR BELT TRACKING SYSTEMS WORK?

Weight and speed are the enemies of belt tracking. The further a belt drifts, the harder it becomes to correct. Engineers studying the issue found that addressing drift immediately making micro-adjustments with automated belt trainers are more effective than standard *vertical edge guides*.

Vertical edge guides are smooth slots or rollers attached to the stringer, positioned perpendicular to the belt's path to prevent the edge from rubbing or cutting into the conveyor structure. Although they reduce severe friction events, they do not prevent misalignment or spillage issues and often allow the belt to roll over itself. Any significant contact with the stringer puts extreme stress on the splice and causes downstream problems that can lead to equipment failure and serious workplace safety concerns.

WHY ARE AUTOMATED TRACKING SYSTEMS EFFECTIVE?

Automated tracking systems like the Martin® Tracker™, with upper units available for the carry side of the belt and lower units for return side, make micro-adjustments using sensing arms with small rollers at the end that detect minor changes in the belt's path. An existing idler set from the existing system is mounted on the steering assembly. Ideally, the rollers have rubber covers for a better grip. The thickness of the belt determines if the tracking device is medium-duty, heavy-duty, or monster-duty.

Upper Trackers are elevated slightly above the other idlers to add more force to the steering assembly.


Alignment provided by the lower Trackers ensures the belt is centered for proper loading.

The force of the belt against the arms in any direction other than the center adjusts the steering assembly proportionally to the belt's drift, guiding it back toward the center. For additional steering power, the assembly elevates the steering idler approximately 10-20 millimeters (0.5 to 0.75 inches) higher than the rolls of the adjacent conventional idlers. The center roll or pivot roll increases the belt's pressure on the tracking device, improving the corrective friction between the belt and the aligning roll.

By adjusting the belt immediately, the material is more likely to shift back to the center rather than move with the drift of the belt, which can worsen the issue. In addition, the downstream benefit is at the discharge zone, where the belt contacts the center of the head pulley and the material stream releases uniformly down the transfer chute with less spillage. Centered discharge also enables scrapers to work more effectively at cleaning the belt.

Another technique to improve performance is to install a return belt-training system with a conventional return idler above the belt, upstream of the tracking device, to push the belt down, increasing the force on the training idler and allowing it to work more effectively.

WHERE TO PLACE AUTOMATED BELT TRACKING DEVICES

Ideally, the upper tracking device should be installed after the load zone on belts wider than 42 inches (1000 mm). The force of the drop from the transfer chute and subsequent vibration can cause material – especially large raw material – to shift through the loading, settling, and stilling zones, putting more weight on one side. Due to a slight amount of belt sag, material also slightly shifts when the belt encounters idlers down the conveyor path. By adjusting the belt directly after leaving the enclosure, the material stream is steered to the center.

Some longer conveyors may require additional units to retain alignment. To avoid units competing and contradicting each other's steering action, they should be positioned approximately 20 to 50 meters (70 to 160 ft) apart. The difference depends on the weight and size of the conveyed material. To ensure the material enters the discharge zone centered, conveyor maintenance experts recommend that a unit should be placed close to the discharge zone.

Proper return roller (or lower tracking device) placement is critical. This ensures the belt encounters the takeup or gravity pulley correctly. Although there may be some drift due to sag, the belt is flat on the return, so crowned rollers that are wider at the center help train the belt back to center.

Maintenance experts recommend installing a lower tracking device approximately five times (5x) the belt width in distance before the tail pulley. This is essential for ensuring the belt enters the loading zone correctly aligned for efficient loading.

LINING UP TO SAFETY AND EFFICIENCY

Why is belt tracking so important? Safety is the main concern. A broken splice can put nearby workers in serious danger. Belt fires traveling at several meters per second can ignite an entire operation before anyone can adequately react.

Aside from lost production due to unscheduled downtime, there are also associated spillage cleanup costs, clouds of dust, and broken equipment. Mistracking is like a pest infestation. Ignoring it makes it worse and in-house solutions rarely work, so in most cases, a professional and lasting solution is required. Automated belt tracking offers peace of mind, less maintenance, safety, and a quick return on investment.

AUTHOR

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As program manager and lead instructor for Martin Engineering's FOUNDATIONS™ Training Workshops, Jerad Heitzler is a leader in helping the industry learn how to make the handling of bulk materials cleaner, safer, and more productive. He started with Martin Engineering as a Customer Development Representative in 2006. He soon realised his love for presentations and for teaching about conveyor systems, and so in 2010 took over management and development of the company's FOUNDATIONS™ Workshop program. Under his leadership, the program has expanded to offer several levels of conveyor improvement workshops around the world

Transformational tyre technology: improving mining performance

Tyre technology has quietly become one of the most transformative levers for improving mining performance. Modern mines operate in environments that punish equipment – abrasive surfaces, extreme loads, long haul cycles – and tyres sit at the centre of that stress. Advances in materials science, digital monitoring, and tyre engineering are giving mining operators something they've always wanted: greater control over productivity, safety, and cost.

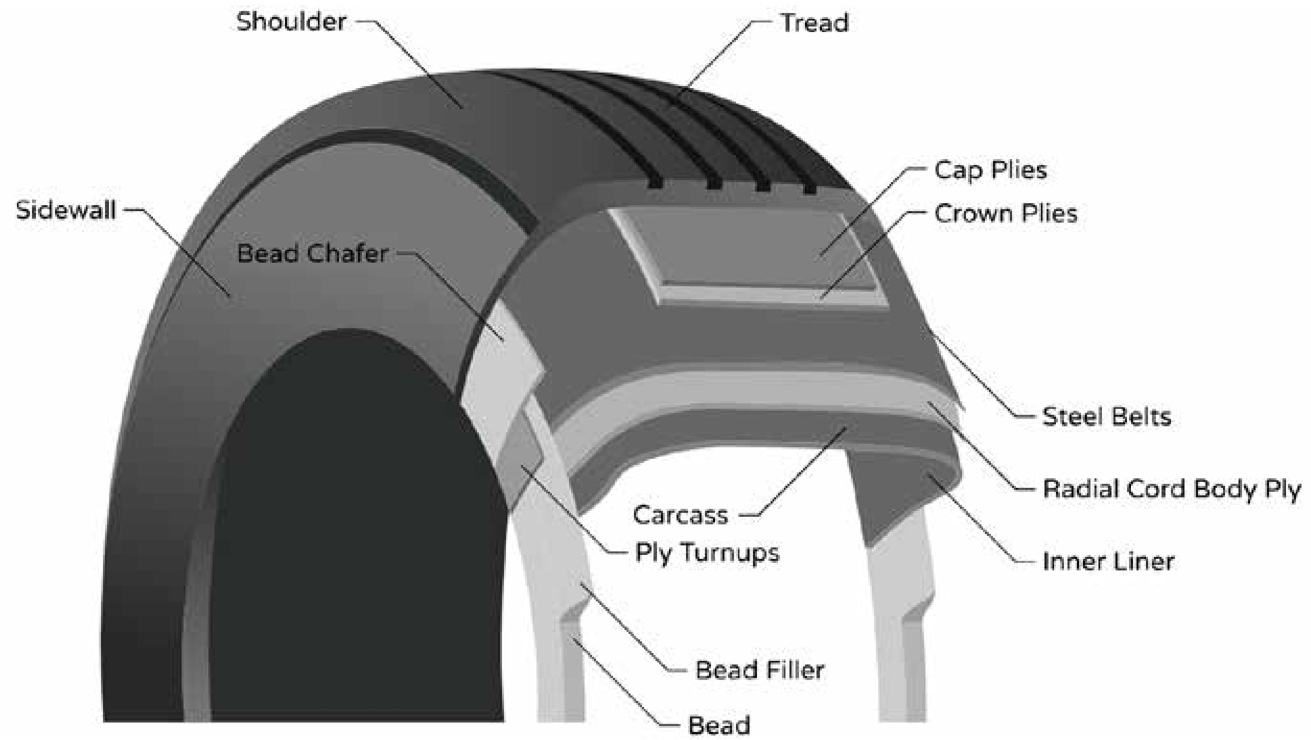
Smart tyre compounds now last longer under heat and load, reducing unplanned downtime and extending the life of haul trucks and loaders. Real-time pressure and temperature monitoring helps operators prevent failures before they happen, protecting both people and assets. Even tread design has evolved to improve traction on loose or uneven ground, cutting cycle times and fuel burn. When you add in data analytics that optimise tyre rotation and replacement schedules, tyres shift from being a consumable to a strategic asset.

Mining companies are under pressure to deliver more with less – less fuel, less maintenance, less risk. Tyre technology is stepping up as a surprisingly powerful contributor to that goal.

Gordon Barratt of Mining & Quarry World takes a detailed look at how Tyres are transforming mining.

A modern mining tyre is a highly engineered structure built to withstand some of the harshest mechanical and environmental stresses found in any industry. Although it appears from the outside to be a simple mass of rubber, its internal architecture is a layered system designed to manage heat, absorb impact, carry immense loads, and maintain stability across unpredictable terrain. Understanding this structure helps explain why tyre technology has become such a critical component of mining performance.

The outermost layer is the tread, formed from advanced rubber compounds that resist heat, cuts, and abrasion. Mining environments expose tyres to sharp rock, heavy braking, and long haul cycles, so the tread must balance durability with traction. Deep lugs and self-cleaning



channels are often moulded into the design to maintain grip on loose or muddy surfaces while shedding debris that could accelerate wear. Beneath the tread lies the under-tread or cushion layer, a shock-absorbing zone that helps dissipate heat and soften the impact of rough haul roads. This layer plays a vital role in preventing internal damage and reducing the risk of heat-related failures.

Below the cushion layer sits the steel belt package, a series of high-tensile steel cords arranged in multiple layers. These belts stabilise the tyre, help it maintain its shape under extreme loads, and provide a protective barrier against punctures. In ultra-class haul truck tyres, the belt package can be several centimetres thick, reflecting the enormous forces these tyres must endure. Supporting the belts is the carcass, or body ply, which forms the structural backbone of the tyre. Made from steel or synthetic fabric cords embedded in rubber, the carcass determines the tyre's load-carrying capacity and flexibility. Radial constructions, now common in mining, use cords arranged perpendicular to the tread, improving heat dissipation and ride quality.

The sidewalls of a mining tyre are reinforced with tough rubber compounds and additional plies to resist cuts and impacts. They must flex enough to absorb shocks yet remain strong enough to stabilise the tyre during heavy cornering or uneven loading. At the base of the tyre, the bead bundle anchors the entire structure to the rim. This component consists of thick steel bead wires that prevent slippage under massive torque and ensure the tyre remains securely seated even under extreme stress.

Inside the tyre, an airtight inner liner acts as the modern equivalent of an inner tube. It maintains consistent air pressure, which is essential for controlling heat, supporting load, and extending tyre life. Increasingly, mining tyres also incorporate embedded sensors within their internal layers. These sensors monitor pressure, temperature, load, and impact forces, transmitting real-time data to digital monitoring systems. This integration of materials engineering and digital intelligence allows operators to detect problems early, optimise tyre performance, and reduce the risk of catastrophic failures.

The structure can be visualised as a series of concentric layers, each with a specific function: the tread for traction and durability, the belts for stability, the carcass for strength, the sidewalls for protection and flexibility, the bead for secure mounting, and the inner liner for pressure retention. Together, these components form a sophisticated system that enables mining equipment to operate safely and efficiently in some of the world's most demanding conditions.

HOW ADVANCING TYRE TECHNOLOGY IS TRANSFORMING MINING OPERATIONS

Mining has always pushed machinery to it's limits, and nowhere is that more evident than in the tyres that carry the industry's heaviest loads. Once viewed simply as consumables, tyres have evolved into engineered systems that blend advanced materials, digital intelligence, and data-driven management. This shift is reshaping how mines operate, improving safety, reducing costs, and unlocking new efficiencies across entire fleets.

Modern mining tyres rely on highly engineered rubber compounds that are very different from the simple natural-rubber blends used decades ago. Manufacturers now design compounds that can survive extreme heat, enormous loads, abrasive rock, and long haul cycles without breaking down. While each company guards its exact formulas, several types of advanced compounds are widely used across the industry.

One of the most important is heat-resistant synthetic rubber, often based on blends of butadiene rubber (BR) and styrene-butadiene rubber (SBR). These materials cope far better with the intense heat generated during long, fully loaded hauls. They resist thermal degradation, which helps prevent blowouts and extends tyre life. Many mining tyres also incorporate natural rubber for elasticity and tear resistance, but it is usually combined with synthetics to balance durability with flexibility.

Another major development is the use of cut- and chip-resistant compounds. These are reinforced with specialised polymers and fillers that help the tread withstand sharp rocks and abrasive surfaces. In open-pit mines, where tyres constantly encounter jagged edges, these compounds significantly reduce surface damage and slow the rate of wear.

Modern compounds also rely heavily on reinforcing fillers, especially carbon black and increasingly silica. Carbon black strengthens the rubber and improves heat dissipation, while silica can reduce rolling resistance and improve traction. Some manufacturers now use recovered carbon black from recycled tyres, which supports sustainability goals without compromising performance.

In ultra-class haul truck tyres, the sidewalls and bead areas often use high-modulus rubber compounds designed to resist deformation under massive loads. These compounds are engineered to remain stable even when the tyre is carrying hundreds of tonnes, helping maintain structural integrity and preventing bead failures.

A growing area of innovation involves nano-reinforced compounds, where nanoparticles – such as nano-clays or carbon nanotubes – are added to improve strength, heat resistance, and elasticity. Although still emerging, these materials point toward the next generation of mining tyres that last longer and perform more consistently.

Digital monitoring laid the foundation for a revolution in tyre management, but the real leap forward came when software and artificial intelligence began interpreting that data. Instead of simply displaying tyre pressures or temperatures on a dashboard, modern systems now analyse millions of data points to understand how tyres behave under different loads, speeds, road conditions, and operator styles. This shift has turned tyre management into a predictive, intelligent discipline that directly improves safety, productivity, and cost efficiency across mining operations.

Software platforms collect data from sensors embedded in the tyre or mounted on the rim, then combine it with information from haul-truck payload systems, fleet-management tools, and even weather or road-condition reports. This integration allows the system to build a complete picture of the forces acting on each tyre throughout a shift. Artificial intelligence models then process this information to identify patterns that would be impossible for a human to detect. For example, a tyre might show a subtle rise in temperature during a specific section of the haul road, or a particular operator might consistently generate higher sidewall stress during cornering. AI highlights these trends and recommends corrective actions long before they become operational problems.

Predictive maintenance is where AI delivers its most powerful impact. Instead of relying on fixed rotation schedules or visual inspections, software can now forecast the remaining life of each tyre with remarkable accuracy. It does this by analysing wear rates, heat cycles, load histories, and impact events. Mines can schedule tyre changes during planned downtime rather than reacting to failures, which reduces disruptions and improves fleet availability. This level of foresight also helps mines optimise their tyre inventory, avoiding both shortages and unnecessary stockpiling.

Artificial intelligence also plays a key role in operator coaching. By analysing how different driving behaviours affect tyre stress, the system can provide targeted feedback

to operators. Excessive cornering speed, harsh braking, or over-aggressive acceleration all contribute to premature tyre wear. AI-driven coaching tools translate complex data into simple guidance that helps operators adjust their driving style. Mines that have adopted these systems often see significant improvements in tyre life and fuel efficiency.

Another major advantage comes from route optimisation. AI can analyse tyre-stress data across different haul routes and identify sections of road that consistently cause overheating, vibration, or impact damage. Maintenance teams can then prioritise road repairs based on real tyre-health data rather than guesswork. In some operations, this has led to smoother haul roads, faster cycle times, and a measurable reduction in tyre failures.

As autonomous haulage becomes more common, software and AI are becoming even more deeply embedded in tyre management. Autonomous trucks rely on tyre data to adjust speed, braking, and cornering in real time. AI models help these systems choose the safest and most efficient routes, avoid conditions that could damage tyres, and maintain optimal pressures for stability and traction. In this environment, tyres are no longer passive components but active inputs into the vehicle's decision-making process.

The combination of digital monitoring, software intelligence, and AI has transformed tyres from one of mining's most unpredictable consumables into a highly manageable asset. Mines now have the ability to anticipate problems, optimise performance, and extend tyre life in ways that were unimaginable a decade ago. This integration of physical engineering and digital intelligence is one of the clearest examples of how modern mining is evolving into a smarter, safer, and more data-driven industry.

Recycling and retreading technologies are also advancing rapidly. High-precision retreading gives OTR tyres a second or even third life, reducing both cost and environmental impact. End-of-life tyres can be processed through pyrolysis or devulcanisation to recover rubber, carbon black, and oil, supporting circular-economy initiatives within mining regions. As sustainability expectations rise, these technologies help mines reduce waste and demonstrate responsible resource management.

Tyre technology may not always be the most visible innovation in mining, but its impact is profound. By combining advanced materials, intelligent monitoring, and data-driven management, modern tyres are helping mines operate more safely, efficiently, and sustainably. As the industry continues to evolve, tyres are no longer just supporting the load – they're helping drive mining's next generation of performance.

RECYCLING

Recycling tyres has become far more than an environmental gesture for the mining industry. It is evolving into a strategic advantage that strengthens operational resilience, reduces costs, and supports the sector's push toward more sustainable production. As mines grapple with rising tyre prices, tighter regulations, and growing pressure to reduce waste, tyre-recycling technologies are stepping in with practical, measurable benefits.

TURNING WASTE INTO USABLE RESOURCES

Mining operations consume enormous volumes of off-the-road (OTR) tyres, many of which weigh several tonnes and are notoriously difficult to dispose of. Modern recycling processes – such as pyrolysis, shredding, and devulcanisation – convert these end-of-life tyres into valuable products like rubber crumb, steel, carbon black substitutes, and even fuel oils. Mines can reintegrate some of these materials into their own operations, for example in haul-road construction or conveyor-belt manufacturing. This closes the loop and reduces reliance on virgin materials.

LOWERING ENVIRONMENTAL AND REGULATORY BURDENS

Stockpiling or burying tyres is increasingly restricted, and many jurisdictions now require responsible disposal. Recycling helps mines stay ahead of compliance requirements while reducing the environmental footprint of their operations. By diverting tyres from landfills and reducing the need for new raw materials, mining companies demonstrate tangible progress toward sustainability targets – something investors and communities are watching closely.

REDUCING COSTS AND IMPROVING SUPPLY SECURITY

OTR tyres are expensive, and global supply can be volatile. Recycling programmes help stabilise costs by recovering materials that can be reused or sold. Some mines partner with recycling firms to create local processing facilities, cutting transport costs and ensuring a reliable outlet for worn tyres. In regions where tyre shortages have disrupted production in the past, recycling adds a layer of supply-chain resilience.

SUPPORTING INNOVATION IN TYRE DESIGN

Manufacturers are increasingly incorporating recycled rubber and carbon black into new tyre compounds. This not only reduces the environmental impact of tyre production but also encourages innovation in durability and heat resistance – qualities that directly benefit mining fleets. As recycled materials become more consistent and high-quality, the industry gains access to tyres that perform better and last longer.

STRENGTHENING COMMUNITY AND INDUSTRY PARTNERSHIPS

Tyre-recycling initiatives often involve collaboration between mining companies, local governments, and specialised recyclers. These partnerships create jobs, stimulate regional economies, and build goodwill in communities that host mining operations. In some cases, recycled tyre products – such as mats, road surfaces, or construction materials – are used in local infrastructure projects, extending the benefits beyond the mine gate.

Recycling tyres is no longer a peripheral sustainability effort; it is becoming a core component of efficient, responsible mining. By transforming a difficult waste stream into a source of value, the industry is proving that environmental stewardship and operational performance can reinforce each other. If you want, I can help you turn this into a more formal report or tailor it to a specific mining company or region.

Tyre technology is one of those behind-the-scenes innovations that has quietly reshaped how modern mines operate. When you look at real-world examples, the impact becomes very tangible. Several mining companies have published data showing how smarter tyres, better monitoring, and improved maintenance strategies translate directly into productivity gains, cost reductions, and safer operations.

REAL-WORLD EXAMPLES AND CASE STUDIES

1. BHP – Extending Haul Truck Tyre Life with Real-Time Monitoring
    - BHP introduced advanced tyre-pressure monitoring systems (TPMS) across parts of its Australian iron ore fleet.
    - By tracking heat, pressure, and load in real time, they reduced catastrophic tyre failures and extended tyre life by several hundred hours.
    - The company reported fewer unplanned stoppages and improved haul truck availability, which directly increased output per shift.

2. Rio Tinto – Autonomous Haulage + Tyre Optimisation
    - Rio Tinto's autonomous haul trucks in the Pilbara rely heavily on tyre data to optimise speed, braking, and cornering.
    - Tyre wear became more predictable, and the company saw a measurable reduction in uneven wear patterns.
    - This allowed them to extend rotation intervals and reduce tyre consumption, which is a major cost in large open-pit operations.

3. Vale – Heat-Resistant Compounds in Brazilian Nickel Mines
    - Vale adopted new heat-resistant tyre compounds for underground loaders (LHDs) operating in high-temperature zones.
    - The tyres maintained structural integrity under extreme thermal stress, reducing blowouts and improving operator safety.
    - The change also cut tyre-related downtime by double-digit percentages.

4. Anglo American – Data-Driven Tyre Management Programs
    - Anglo American partnered with tyre manufacturers to implement predictive analytics for tyre wear.
    - Using haul road conditions, payload data, and tyre temperature readings, they built models that forecast tyre failures before they occurred.
    - This led to more efficient tyre rotation schedules and fewer emergency replacements, improving fleet utilisation.

5. Komatsu & Michelin – Integrated Tyre and Equipment Solutions
    - Some mines using Komatsu haul trucks with Michelin's MEMS (Michelin Earthmover Management System) reported:
      Lower fuel burn due to optimised inflation
    - Longer tyre life from better load distribution
    - Improved traction on wet or uneven surfaces
    - The combination of OEM equipment data and tyre telemetry created a more holistic view of fleet performance.

6. South African Platinum Mines – Tread Design for Harsh Terrain
    - Mines operating on sharp, abrasive rock adopted tyres with reinforced sidewalls and deeper tread patterns.
    - These tyres resisted cuts and punctures far better than previous generations.
    - The result was fewer tyre changes in remote areas, improving safety and reducing the need for technicians to work in hazardous zones.

7. Canadian Oil Sands – Ultra-Class Truck Tyre Innovations
    - Oil sands operations are notorious for extreme loads and abrasive conditions.
    - The introduction of ultra-class tyres with improved bead construction and stronger carcasses allowed trucks to carry heavier loads without compromising tyre integrity.
    - Operators reported improved cycle times and reduced cost per tonne.

WHAT THESE CASES HAVE IN COMMON

Across all these examples, three themes stand out:

1. **Predictive Maintenance**
   Tyre sensors and analytics help mines move from reactive to predictive maintenance, reducing failures and improving planning.

2. **Longer Tyre Life**
   Better compounds, smarter tread patterns, and optimised inflation extend tyre life – critical when a single haul truck tyre can cost tens of thousands of dollars.

3. **Higher Productivity and Safety**
   Fewer blowouts, fewer roadside repairs, and more consistent truck performance translate into safer, more efficient operations.

Ventilation challenges

VENTILATION IN UNDERGROUND MINING

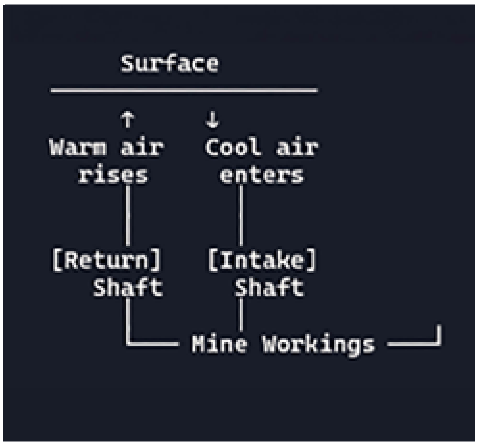
Effective ventilation is a foundational requirement for safe and productive underground mining. Without controlled airflow, hazardous concentrations of methane, carbon monoxide, respirable coal dust, and other noxious gases can accumulate, creating conditions conducive to explosions, fires, and acute or chronic health impacts. Maintaining adequate oxygen levels and ensuring the continuous dilution and removal of contaminants are therefore central objectives of any mine ventilation strategy.

Gordon Barratt of Mining & Quarry World takes a look at how Ventilation has developed through the years of mining.

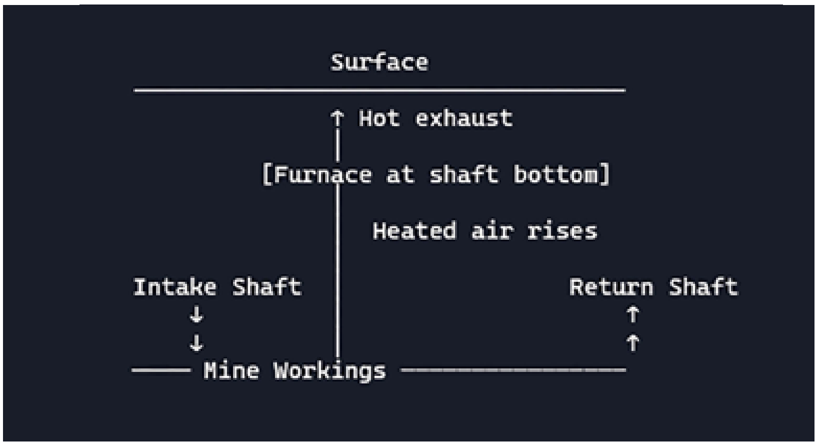
This article examines the core engineering principles that govern underground ventilation systems, the technologies and design methodologies currently in use, the operational and geological challenges that influence system performance.

THE HISTORICAL DEVELOPMENT OF UNDERGROUND VENTILATION SYSTEMS

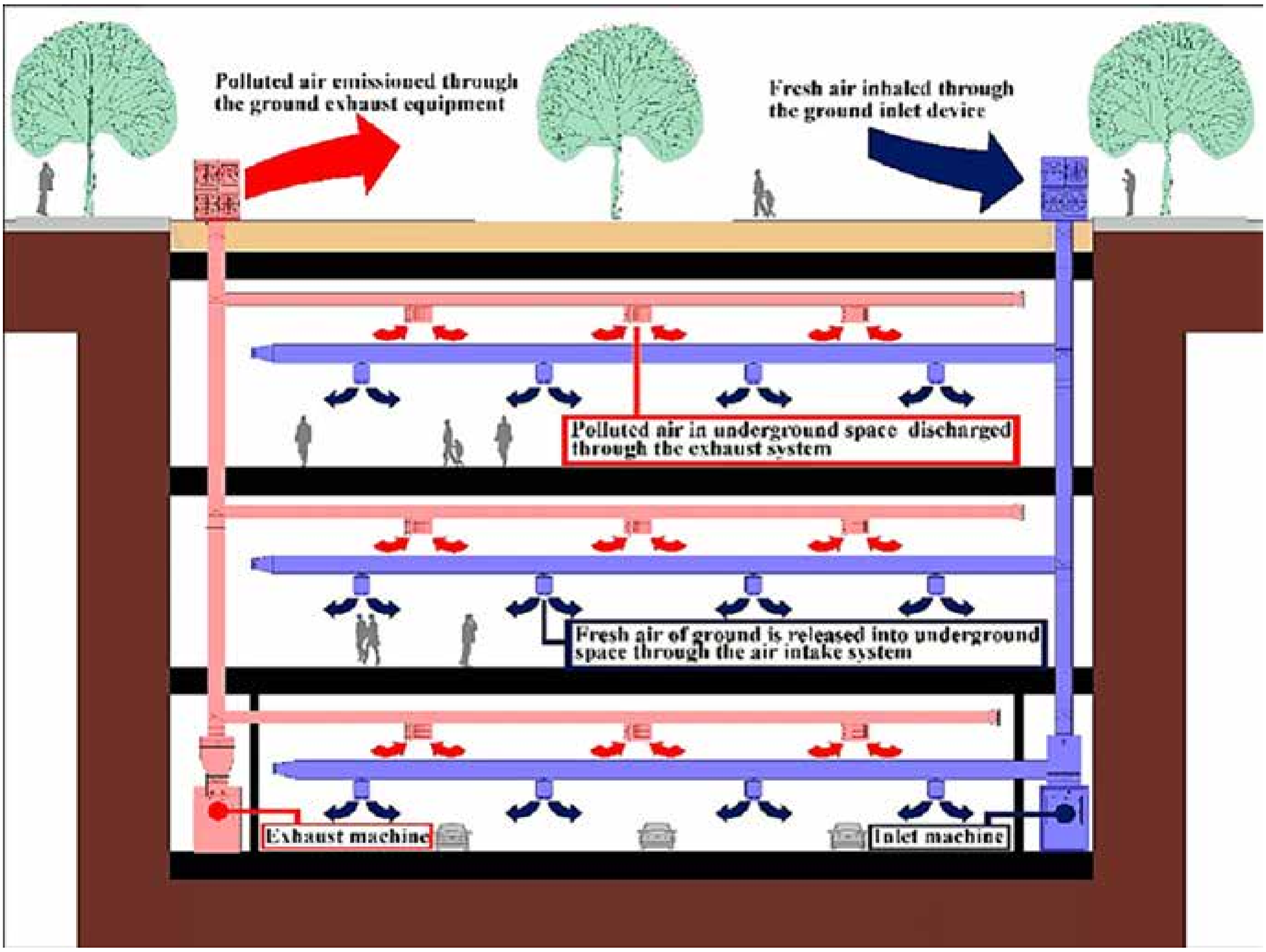
The control of underground atmospheres has been a defining challenge throughout the history of mining. As early miners expanded their workings beyond shallow adits and surface-connected stopes, the need to manage heat, dust, and noxious gases became increasingly apparent. The evolution of ventilation systems reflects both the growing complexity of underground operations and the parallel advancement of engineering knowledge.



Basic Natural Ventilation Using Two Openings



Furnace-Induced Ventilation



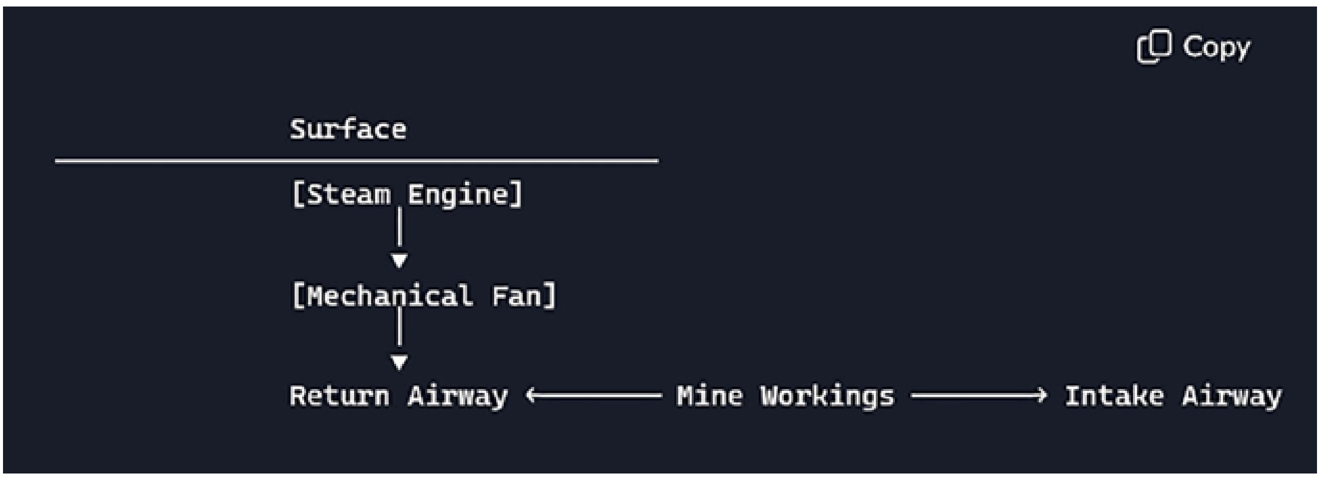
EARLY PRACTICES AND NATURAL VENTILATION

In antiquity, ventilation relied almost entirely on natural draughts. Egyptian, Greek, and Roman miners constructed auxiliary openings – shafts, crosscuts, and small airways – to exploit pressure differentials created by wind and temperature gradients. Although rudimentary, these methods represented the first systematic attempts to control airflow and mitigate the accumulation of smoke, dust, and naturally occurring gases.

THE DEEPENING OF MINES AND THE RISE OF MECHANICAL SOLUTIONS

By the 16th and 17th centuries, European mines were reaching unprecedented depths, and natural ventilation was no longer sufficient. Stagnant air, heat buildup, and the presence of "blackdamp" and "firedamp" became major operational hazards. Miners introduced simple mechanical aids such as hand-operated bellows and furnace ventilation, where heated air rising through a shaft induced airflow through the workings.

The industrial expansion of the 18th century – particularly in coal mining – brought a surge in methane-related explosions. This period marked a turning point: the first large-scale mechanical fans were introduced in Britain, and engineers such as George Stephenson applied steam



Diagam 3 – Early Mechanical Fan Ventilation

power to drive ventilation machinery. These innovations enabled more predictable airflow and significantly reduced the risk of gas accumulation.

TECHNOLOGICAL MATURATION IN THE 19TH AND 20TH CENTURIES

By the late 19th century, ventilation engineering had become a distinct discipline. Purpose-built centrifugal and axial fans replaced earlier furnace systems, offering higher capacities and improved reliability. Flameproof (Ex-rated) designs emerged in response to catastrophic methane explosions, ensuring that ventilation equipment itself did not become an ignition source.

Throughout the 20th century, advances in fluid mechanics, electrical engineering, and materials science transformed ventilation practice. The introduction of auxiliary fans, booster fans, and regulated airways allowed engineers to design complex, multi-branch ventilation networks capable of supporting large-scale mechanised mining. Regulatory frameworks also strengthened, mandating minimum air quantities, gas monitoring, and system redundancy.

THE DIGITAL ERA AND MODERN VENTILATION ENGINEERING

In recent decades, underground ventilation has entered a new phase driven by automation, real-time monitoring, and computational modelling. Sensor networks now provide continuous data on methane, carbon monoxide, airflow, and temperature. Ventilation-on-demand (VOD) systems dynamically adjust air distribution based on equipment activity and gas levels, reducing energy consumption while maintaining safety. Computational fluid dynamics (CFD) has become a standard tool for predicting airflow behaviour, optimising fan placement, and evaluating emergency scenarios.

CONCLUSION

The development of underground ventilation systems reflects the broader trajectory of mining engineering: from empirical practices to scientifically grounded, technology-driven solutions. What began as simple reliance on natural airflow has evolved into sophisticated, automated systems capable of managing complex underground environments. As mines continue to deepen and mechanise, ventilation engineering will remain central to ensuring safe, efficient, and sustainable operations.

CORE FUNCTIONS OF UNDERGROUND MINE VENTILATION

The primary purpose of underground ventilation is to supply clean, breathable air to all working areas while preventing the accumulation of hazardous gases, dust, and heat. Key engineering objectives include:

Dilution and Removal of Contaminants

Ventilation must continuously dilute and remove methane, carbon monoxide, blasting fumes, and respirable dust generated during extraction, haulage, and support activities.

Control of Microclimate

Temperature and humidity must be regulated to maintain acceptable working conditions and prevent heat stress, particularly in deep or high-heat-load mines.

Prevention of Gas Ignition

Airflow must be managed to prevent methane layering, minimise ignition potential, and ensure rapid removal of flammable or toxic gases.

REDUCTION OF FIRE AND EXPLOSION HAZARDS

Properly directed airflow reduces the likelihood of explosive gas concentrations and supports emergency response strategies in the event of a fire.

GLOBAL APPROACHES TO UNDERGROUND VENTILATION

Ventilation practices vary internationally based on geology, regulatory frameworks, and methane emission profiles.

- United States: Split-ventilation systems are widely used to isolate air circuits and maintain strict control over methane concentrations in gassy coal mines.

- Australia: Dynamic ventilation strategies – periodically altering airflow direction or volume – are applied in high-risk environments to improve gas management and enhance monitoring capability.

These regional approaches illustrate the diversity of engineering solutions employed to maintain safe atmospheric conditions.

VENTILATION PLANNING AND TECHNICAL REQUIREMENTS

A mine ventilation plan must be engineered to reflect site-specific geological, climatic, and operational conditions. Key design requirements include:

Airflow Volume and Velocity Calculations

Air quantity must be allocated per worker and per production unit, with increased airflow required in high-methane mines. Typical design ranges include:

- Low-methane mines: 1–2 m/min
- Moderate-methane mines: 3–6 m/min
- High-methane mines: 20–25 m/min
- Safety and Redundancy

Ventilation systems must remain operational during power failures. Backup generators, auxiliary fans, and integrated monitoring and alarm systems are essential components of a resilient ventilation network.

Intake and Exhaust Systems

Mechanical ventilation equipment must be certified explosion-proof (Ex-proof) to prevent ignition of methane-air mixtures. This requirement is particularly critical in methane-drainage or high-gas-emission operations.

ADVANCES IN VENTILATION TECHNOLOGY AND RESEARCH

Modern ventilation engineering increasingly relies on digital tools. Computational fluid dynamics (CFD), real-time sensor networks, and automated control systems enable continuous monitoring of airflow, gas concentrations, and pressure differentials. Research such as that by McPherson et al. (2015) demonstrates the value of simulation models for predicting methane behaviour and optimising ventilation layouts, contributing to more robust safety strategies.

PRACTICAL APPLICATIONS AND INTERNATIONAL EXAMPLES

Several countries have implemented innovative ventilation configurations to improve system performance:

Russia: Multi-fan systems operating in parallel provide more uniform airflow distribution across extensive underground networks.

Russia's deep and extensive underground mines – particularly in the Kola Peninsula, Norilsk region, and parts of Siberia – have long relied on multi-fan ventilation systems operating in parallel to maintain stable airflow across vast, branching networks. These systems are designed to overcome the limitations of single-fan configurations, especially in mines with:

- Long haulage drifts
- Multiple production blocks
- High heat loads
- Complex, multi-level layouts

Parallel fan operation is a defining feature of Russian ventilation engineering, supported by decades of research from institutions such as the Mining Institute of the Ural Branch of the Russian Academy of Sciences. Studies highlight that single-fan systems are well understood, but multi-fan optimisation remains an active area of research, particularly in Russia's automated ventilation control systems (AVCS).

WHY PARALLEL MULTI-FAN SYSTEMS ARE USED

1. Uniform Airflow Distribution
   Operating several main fans in parallel reduces the pressure differential across any single airway. This prevents over-ventilation of some districts and under-ventilation of others.

2. Redundancy and Reliability
   If one fan requires maintenance, others can maintain minimum airflow without shutting down production.

3. Energy Efficiency
   Parallel operation allows fans to run at lower individual speeds, reducing specific energy consumption – an important factor in Russian mines where ventilation is a major power draw.

4. Compatibility with Automated Control
   Russia's AVCS systems dynamically adjust fan speeds and ventilation door positions to optimise airflow distribution in real time. Multi-fan setups provide the flexibility needed for such optimisation.

SYSTEM ARCHITECTURE

A typical Russian multi-fan parallel system includes:

- Two or more main fans installed on surface bulkheads
- Parallel intake or exhaust drifts feeding into a common airway
- Booster fans in deep or remote districts
- Ventilation doors and regulators controlled by microprocessor-based systems
- Airflow sensors distributed throughout the network
- Automated control algorithms that adjust fan speed and door positions

BASIC PARALLEL FAN CONFIGURATION

Key behaviour:

- Both fans discharge into the same exhaust airway.
- Pressure contributions combine, increasing total airflow.
- If Fan A slows, Fan B compensates automatically under AVCS logic.

AIRFLOW DISTRIBUTION ACROSS MULTIPLE DISTRICTS

Interpretation:

- Parallel fans feed a shared intake network.
- Airflow divides according to airway resistance.
- Automated regulators adjust resistance to maintain required flows.

```
[Fan A] --→\
            \
             +——→ Main Exhaust Drift ———→
            /
[Fan B] --→/
```

```
                 +——————————— District 1
                 |
[Fan A] --→+——+——————————— District 2
           |     |
[Fan B] --→+     +——————————— District 3
```

```
Fan Pressure (P)
^
|        Fan A Curve
|          \
|           \____ Combined System Curve
|           /
|  Fan B  /
+——————————————————————————→ Airflow (Q)
```

```
Surface Level
____________________________________________
   [Fan A] ═════\
                 \
                  +═══ Main Exhaust Shaft ═══⇒
                 /
   [Fan B] ═════/

Level -1 ———————————————— Production Block A
Level -2 ———————————————— Production Block B
Level -3 ———————————————— Production Block C
```

PRESSURE–FLOW RELATIONSHIP IN PARALLEL FANS

Engineering insight:

- Parallel fans increase total airflow at a given pressure.
- The combined curve lies to the right of individual fan curves.
- This is ideal for large mines with high volumetric demand.

Russian AVCS platforms use:

- Real-time airflow modelling
- Microcontroller-based fan and door control
- Optimal air distribution algorithms
- Partial recirculation strategies

These systems automatically determine the best operating parameters for each fan, ensuring uniform airflow and minimising energy consumption.

OPERATIONAL ADVANTAGES IN RUSSIAN MINES

Improved airflow stability

Parallel fans reduce the risk of airflow reversal or instability during fan trips.

Better control of contaminants

Uniform distribution ensures consistent dilution of diesel particulates, methane, and heat.

SCALABILITY

As new levels or blocks are developed, additional fans can be integrated without redesigning the entire system.

LOWER SPECIFIC ENERGY CONSUMPTION

Studies from Russian mines show significant savings when fan motors are modernised and operated under optimised load conditions.

MULTI-LEVEL RUSSIAN MINE LAYOUT WITH PARALLEL FANS

Effect:

Parallel fans maintain consistent pressure across all levels, preventing airflow collapse in deeper blocks.

FUTURE DIRECTIONS IN RUSSIA

- Digital twins for real-time airflow simulation
- AI-driven optimisation of fan speed and regulator settings
- Integration with mine electrification to reduce heat load
- Advanced recirculation systems to reduce intake air requirements

This example highlights the growing emphasis on automation and adaptive control in modern mine ventilation engineering.

CONCLUSION

Ventilation remains one of the most critical components of underground mine safety. Effective systems ensure adequate oxygen supply, control methane and carbon monoxide concentrations, and reduce the likelihood of fires and explosions. Advances in modelling, automation, and sensor technology continue to enhance the reliability and efficiency of ventilation networks. Because each underground mine presents unique geological and operational challenges, ventilation systems must be tailored accordingly to maintain safe and compliant working conditions.

Adapting to rapid modernisation in mining

Mining has long underpinned global economic development, enabling the technological and industrial progress that defines modern society. As a foundational sector, it now faces a pivotal moment: adapting to rapid modernisation, shifting workforce expectations, and intensifying scrutiny around sustainability and ESG performance.

Mining & Quarry World takes a detailed look at the challenges being faced by the mining industry.

THE MODERNISATION IMPERATIVE

Despite clear targets and ongoing investment in digitalisation, sustainability and ESG initiatives, mining leaders continue to grapple with the challenge of repositioning the industry. The sector must evolve from a legacy perception of environmental strain and operational monoculture into one recognised for innovation, inclusivity, and climate responsibility.

The pressures are mounting. Workforce expectations are changing faster than at any point in recent history. Sustainability concerns are reshaping investment decisions. Geopolitical uncertainty is influencing supply chains and capital flows. Collectively, these forces represent one of the most complex operating environments the industry has faced.

DIGITAL TRANSFORMATION ACCELERATED

The shift toward a digitally enabled workforce – accelerated dramatically by the COVID-19 pandemic – has heightened the urgency for operational transformation. Advanced technologies such as artificial intelligence, automation and real-time analytics are increasingly seen as essential to improving productivity, safety and decision-making.

This digital evolution is unfolding in parallel with rising expectations around ESG performance and the global transition to low-carbon systems. Mining organisations must therefore redesign operating models to close skill gaps, strengthen workforce engagement, and embed sustainability into every layer of the business.

A NEW WORKFORCE AND ESG REALITY

To remain competitive, mining companies will need to prioritise diversity, equity, and inclusion, while also accelerating efforts to reduce emissions and environmental impact. These priorities are no longer optional – they are central to attracting talent, securing investment, and maintaining social licence.

LEADERSHIP FOR A TRANSFORMING INDUSTRY

Mining remains a critical driver of global development, but its future depends on how effectively leaders respond to these converging pressures. The sector must cultivate a workforce equipped for digital operations, foster a culture that supports innovation and inclusivity, and implement strategies that deliver measurable ESG progress.

To better understand the needs of today's mining workforce and the actions required to accelerate industry transformation, we engaged with experts and thought leaders across the mining and resources sector. Their insights highlight both the progress made and the steps still needed for mining to thrive in an increasingly progressive and technology-driven world.

FLEXIBILITY

Modern work has shifted decisively toward flexibility, with remote and hybrid models now embedded across most industries. Mining, despite its operational complexity, is not exempt from this shift. For a sector dominated by "deskless" workers who operate far from traditional office environments, flexibility has become a strategic requirement rather than an optional benefit. To support this evolution, mining organisations must invest in technologies and systems that enable seamless communication across vast and dispersed worksites. This includes building the facilities, digital infrastructure and policies that make flexible work both practical and equitable for all employees.

SKILLS GAP AND MANAGEMENT

At the same time, the industry must elevate its approach to talent management. Addressing the skills gap requires structured learning systems, targeted development programs and competency-based training that reach both operational and corporate teams. Mentoring, upskilling pathways and opportunities for cross-functional collaboration are essential to building a workforce capable of supporting increasingly digital operations. Flexible learning models – accessible on demand and across locations – will be central to maximising workforce development and ensuring that employees can grow alongside the technologies transforming the sector.

CULTIVATING CULTURE

However, technology and training alone are not enough. Sustainable transformation depends on cultivating the right organisational mindset. Mining is fundamentally a people-driven industry, and the success of any new system or process hinges on effective change management. Clear communication, structured frameworks, and visible leadership support are critical to ensuring that workers understand the purpose behind change and feel equipped to adopt new ways of working. Without this alignment, even the most advanced technologies will fall short of their potential.

ESG

As the industry modernises, ESG considerations must be embedded into every strategic decision rather than treated as an afterthought. Investors, communities, and governments are raising expectations, and mining companies must respond by addressing the root causes of environmental, social and governance risks. Strong governance, transparent policies, and an engaged workforce are essential to delivering meaningful ESG outcomes and maintaining social licence in an increasingly scrutinised operating environment.

DIVERSITY, EQUITY, AND INCLUSION

Diversity, equity, and inclusion also play a central role in shaping the future of mining. Ensuring fair treatment, equal opportunity and safe working conditions is fundamental to attracting and retaining talent. This includes addressing issues such as sexual harassment, implementing inclusive policies for workers from diverse backgrounds and adopting gender-neutral processes. Leaders must develop the cultural awareness and sensitivity required to manage a workforce that is increasingly varied in both geography and demographics.

Together, these shifts signal a profound transformation in how mining organisations must operate. Flexibility, talent development, cultural readiness, ESG integration and genuine inclusion are no longer peripheral considerations – they are core leadership responsibilities. The companies that embrace these priorities will be best positioned to build a resilient, future-ready workforce and sustain long-term competitiveness in a rapidly evolving industry.

Only a few years ago, the idea of implementing remote or hybrid work in industries reliant on physical operations – mining included – seemed unrealistic. The arrival of the global pandemic in 2020 fundamentally altered that assumption. Flexible working arrangements shifted from a theoretical concept to an operational necessity, and organisations discovered that remote work could be effective not only for office-based staff but also, in certain contexts, for hourly and deskless employees. In many cases, productivity increased rather than declined, challenging long-held beliefs about where and how work must be performed.

As attitudes toward workplace environments evolve, mining leaders must determine how best to support a workforce whose expectations have changed. While many roles – particularly shift-based and site-critical positions – will always require physical presence, the industry can no longer treat digital enablement and flexible arrangements as exceptions. Embracing new technologies, redesigning workflows and modernising communication systems are now essential to meeting the needs of a diverse and distributed workforce.

Encouragingly, mining organisations are already responding to this shift. Leaders across the sector recognise that flexibility is becoming a core component of workforce strategy, not a temporary accommodation. One industry survey found that approximately 68% of mining companies now view flexible working arrangements as essential for workforce success. This reflects a broader understanding that empowering employees – whether they are deskless or desk-bound – supports not only productivity but also retention, engagement, and long-term organisational resilience.

Mining is a deeply established industry, and with that legacy

often comes a natural resistance to change. Yet in a world that is evolving at unprecedented speed, even the most entrenched systems must adapt. The sector can no longer rely solely on traditional processes; it must be prepared to respond to new expectations, new technologies and a workforce whose needs are shifting rapidly.

CHANGE MANAGEMENT.

Change management has therefore become a critical component of mining performance and resource strategy. Creating the right environment for large-scale transformation is challenging, but it is essential. Leaders must recognise that mining is fundamentally a people-driven industry. Culture plays a central role in helping both office-based and deskless workers feel empowered, informed and aligned as the organisation evolves. A strong culture provides autonomy while also acting as a stabilising guide rail during periods of transition.

This requires a shift away from the traditional top-down communication model that has long defined mining operations. Deskless and hourly workers, in particular, often have limited access to conventional communication channels, making one-way directives far less effective. Two-way communication – timely, transparent, and accessible – is essential to ensuring that all employees understand the purpose behind change and feel included in the journey.

With the right employee experience solutions, mining leaders can bridge the gap between corporate and operational environments. Modern digital tools make it possible to engage workers wherever they are, strengthen alignment across teams and improve the overall employee experience. When workers feel connected, informed, and supported, they are far more likely to embrace new technologies, adopt new processes and contribute to sustainable organisational progress.

The importance of ESG in today's mining landscape is impossible to ignore. Investors and shareholders are applying increasing pressure on companies to accelerate decarbonisation and demonstrate genuine commitment to environmental responsibility. Recent data shows that more than six in ten mining and metals investors are reluctant to invest in organisations that fail to meet their decarbonisation targets or show insufficient progress toward them. This shift in investor sentiment has prompted mining leaders to strengthen their sustainability strategies, establish dedicated committees and enhance the depth and transparency of their reporting.

Despite these efforts, the industry continues to grapple with a persistent stigma. Mining is often viewed through the lens of its historical environmental impact, even as it plays a critical role in enabling the global green transition by supplying the raw materials essential for renewable technologies. This disconnect underscores the need for clearer, more consistent communication. Workers, communities, and stakeholders must understand not only what actions are being taken, but why they matter and how they contribute to broader climate goals.

Environmental progress alone, however, is not enough. The social and governance dimensions of ESG are equally important. Prioritising health and safety, strengthening corporate policies and ensuring that workers' needs are met are fundamental to building trust and maintaining a resilient workforce. When employees feel protected, informed, and valued, they are more likely to support and advance the organisation's ESG objectives.

Ultimately, an effective ESG strategy cannot be built in isolation from the workforce. Progress depends on engaging employees at every level, ensuring they understand the organisation's commitments and empowering them to contribute to meaningful change.

By aligning environmental ambition with strong social practices and robust governance, mining companies can strengthen their ESG performance and reinforce their role in a sustainable future.

Here is a polished, executive-level essay version of your text, aligned with the tone and structure of the rest of your article:

EQUAL OPPORTUNITIES

For many decades, mining was widely regarded as a man's world – an industry where women faced significant barriers to entry, from hostile working cultures to the risk of sexual harassment and a lack of inclusive policies. These challenges made it difficult for women, and for many under-represented groups, to build long-term careers in the sector. Over time, however, the industry has begun to shift. A stronger emphasis on diversity, equity and inclusion (DEI) is reshaping expectations and opening doors that were once firmly closed.

DEI is now recognised as essential to the future of mining. Ensuring that workers – regardless of gender, ethnicity, or background – are treated fairly and given equal opportunity is not only a moral imperative but a business one. A growing body of research shows that diverse workforces outperform their less diverse counterparts. Companies with above-average diversity generate significantly more innovation-related revenue – 45% compared with 26% – a difference that translates directly into stronger financial performance. In an industry where innovation is increasingly tied to digital transformation, operational efficiency and sustainability, this advantage is particularly meaningful.

MODERN WORKFORCE MANAGEMENT

Modern workforce management therefore requires more than simply hiring diversely. It demands policies and processes that meet the needs of all employees, wherever they work and whatever their background. By adopting management approaches that are inclusive and adaptable, mining organisations can create environments where people from different cultures, identities and locations collaborate effectively. This not only strengthens team performance but also enhances problem-solving, creativity and organisational resilience.

As mining continues to evolve, embracing DEI is no longer optional. It is a strategic necessity – one that supports workforce attraction and retention, strengthens organisational culture, and positions the industry to thrive in a world that increasingly values fairness, representation, and innovation.

SIGNIFICANT CHALLENGES

While mining has made meaningful progress in improving its appeal as both a career path and a socially responsible industry, the reality is that significant challenges remain. Despite rapid growth in technical capability across the sector, a severe talent shortage continues to threaten long-term competitiveness. The issue is particularly acute in regions such as Australia, where tertiary enrolments in mining engineering have fallen by 63% since 2014, even as demand for new workers is projected to rise by approximately 24,400 by 2026. Addressing this labour gap is now a matter of urgency.

To respond effectively, industry leaders must focus on attracting new talent while simultaneously reskilling and upskilling the existing workforce. This is especially critical for hourly and deskless workers, who often have fewer opportunities for structured development. Implementing robust learning management systems and targeted talent programs can help bridge this gap by providing accessible pathways for growth. Mentoring, technical training, upskilling initiatives, and networking opportunities all play a vital role in building a workforce capable of supporting the industry's digital and operational evolution. Flexible learning models – designed to accommodate varied schedules, locations, and job types – are essential to ensuring that development is both practical and inclusive.

By creating an environment where continuous learning is encouraged and supported, mining companies can strengthen organisational capability and improve long-term strategic positioning. This investment in people not only helps address immediate labour shortages but also reinforces mining's role as a central contributor to societal development. As the industry becomes more progressive, technologically advanced, and worker-focused, it will be better equipped to attract the next generation of talent and sustain its relevance in a rapidly changing world.

It is increasingly evident that the modern workforce requires management approaches that differ dramatically from those of the past. Today's mining organisations must rely on smart, data-driven communication systems that use real-time insights, advanced analytics, and automation to create personalised workflow experiences and support greater adaptability across all roles. These capabilities are no longer optional; they are fundamental to building a workforce that can operate efficiently in a rapidly evolving environment.

At the same time, mining is not solely defined by its systems and processes – it is defined by its people. For the industry to achieve the outcomes it seeks, all workers, whether deskless or office-based, must have access to the same level of shift flexibility, attendance accuracy, learning opportunities and workflow optimisation. Equity in these areas is essential to ensuring that every employee can contribute effectively and feel supported in their role.

Encouragingly, leaders across the mining and resources sector recognise that a significant shift has taken place. Many have already begun adjusting their thinking and investing in more progressive approaches to workforce engagement and management. We are seeing deliberate efforts to extend flexibility to deskless workers through modern tools and communication platforms that connect teams across sites, regions, and communities. Diversity and inclusivity are also gaining traction, with organisations working to build cultures where ESG priorities are embedded and employees feel both supported and challenged.

Transformation, however, is a long-term journey. The industry still has work to do to reshape perceptions and fully realise the benefits of a modern, people-centred operating model. But if leaders remain focused on strengthening workplace culture through effective change management, advancing ESG and DEI commitments, and developing and attracting the right talent, mining will be well positioned to enter its next phase of evolution. By unlocking the full potential of its workforce, the sector can continue to play a central role in global development while becoming more progressive, resilient, and future-ready.

Evolution and emerging trends in comminution technology for modern mining operations

Crushing and comminution processes remain fundamental to the performance and economics of mining operations. As ore bodies become more complex and grades decline, the ability to efficiently reduce run-of-mine (ROM) material to optimal feed sizes for downstream processing has become increasingly critical. Effective size reduction directly influences throughput, liberation characteristics, energy consumption, and overall plant productivity.

Gordon Barratt of Mining & Quarry World explores how crushers and comminution processes play a crucial role in improving mining performance and overall operational economics.

Historically, the mining sector relied on manual or low-mechanisation methods – such as hand hammering and basic mechanical breakers – to fragment rock. These early techniques offered limited control over product size distribution and required significant labour input. The industrialisation of mining introduced more robust mechanical systems, including jaw crushers, gyratory crushers, and cone crushers, which provided higher capacity, improved reliability, and more consistent reduction ratios.

Over the past several decades, comminution technology has advanced substantially. High-pressure grinding rolls (HPGR) have become a key innovation, offering improved energy efficiency, enhanced mineral liberation, and reduced operational wear compared to traditional SAG milling in many applications. Modern cone and jaw crushers now incorporate hydraulic adjustment systems, variable speed drives, and advanced liner designs to optimise performance across a wide range of ore types.

Recent developments have accelerated the integration of digitalisation and automation into crushing circuits. AI-driven optimisation platforms, machine-learning-based predictive maintenance, and real-time condition monitoring systems enable operators to fine-tune crusher settings, detect anomalies, and maximise uptime. Energy-efficient designs – such as optimised chamber geometries, reduced idle power draw, and intelligent load management – support both cost reduction and sustainability objectives.

Looking ahead, the trajectory of crushing technology points toward fully autonomous comminution circuits, increased use of digital twins for process simulation, and further reductions in specific energy consumption. These innovations are reshaping the mining industry's approach to efficiency, environmental stewardship, and long-term profitability.

This article examines the historical progression, current state-of-the-art technologies, and future trends in mining crushing systems, highlighting the engineering advancements that continue to redefine operational performance across the sector.

HISTORICAL AND MODERN EVOLUTION OF CRUSHING TECHNOLOGY IN MINING

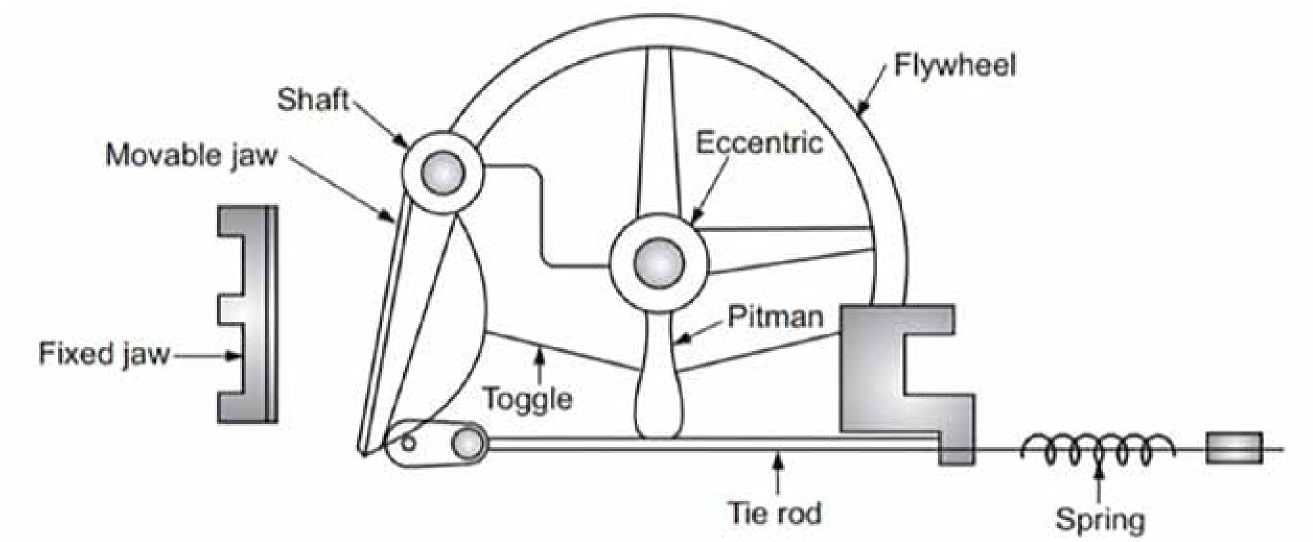
Crushing has long been a foundational process in mining, serving as the first major step in the comminution chain and directly influencing downstream efficiency, mineral

Early rock breaking techniques

liberation, and overall plant performance. The evolution of crushing technology reflects broader shifts in mining engineering, from early manual techniques to today's highly automated, sensor-driven systems. Understanding this progression provides valuable context for current design practices and future developments in comminution circuits.

The earliest methods of rock breakage were rooted in manual labour and simple mechanical principles. Ancient miners relied on handheld hammers, stone tools, and chisels to fragment ore, producing extremely low throughput and inconsistent particle sizes. Fire-setting, one of the earliest thermal breakage techniques, involved heating rock faces with wood fires and quenching them with water to induce fracturing through thermal shock. Although effective for certain lithologies, the method was slow, hazardous, and energy-intensive. By the Middle Ages, water-powered and animal-driven stamp mills emerged, offering modest improvements in productivity but still lacking precise control over fragmentation. These early systems were constrained by limited energy transfer efficiency, high labour requirements, and minimal ability to regulate product size distribution, making them unsuitable for large-scale mining operations.

The Industrial Revolution marked a decisive shift toward mechanisation, driven by the availability of steam power and advances in metallurgy. Steam-powered crushers enabled continuous, higher-capacity rock breakage, laying the groundwork for modern primary crushing. The invention of the Blake jaw crusher in 1858 represented a major engineering milestone, introducing a more reliable and controllable mechanism for reducing run-of-mine material. Gyratory crushers soon followed, offering even greater capacity and continuous operation, which made them particularly suitable for large open-pit and underground mines. Mechanical roll crushers and improved stamp mills



Mechanical principles of the Blake Jaw Crusher further enhanced the consistency of crushed product, supporting the expansion of mineral processing and metallurgical industries. This era transformed mining from a labour-intensive craft into an industrialised sector capable of handling significantly larger ore volumes.

The twentieth century brought rapid innovation as electrification, materials science, and the increasing complexity of ore bodies demanded more efficient and robust crushing equipment. Electric motors replaced steam engines, providing more precise control, higher efficiency, and reduced maintenance requirements. The introduction of cone crushers in the early twentieth century revolutionised secondary and tertiary crushing by enabling adjustable settings, improved reduction ratios, and better handling of abrasive ores. Hydraulic systems further enhanced crusher performance by enabling tramp release, hydraulic adjustment, and overload protection, significantly improving safety and reducing downtime. Advances in wear-resistant materials, including manganese steel, high-chrome alloys, and later carbide-enhanced liners, extended equipment life and reduced operational costs. The development of high-pressure grinding rolls (HPGR) in the 1980's represented a major leap in energy-efficient comminution, offering improved mineral liberation and substantially lower specific energy consumption compared to traditional SAG milling in suitable ore types.

In recent decades, automation and digitalization have reshaped the design and operation of crushing circuits. Modern plants increasingly rely on advanced control systems, real-time monitoring, and machine-learning algorithms to optimize crusher performance. Sensors measuring vibration, temperature, power draw, feed characteristics, and liner wear provide continuous data streams that feed into predictive maintenance models and automated control loops. Laser and radar-based level sensors maintain consistent cavity levels, reducing the risk of blockages and ensuring stable operating conditions. Digital twins allow engineers to simulate crusher behaviour under varying ore conditions, enabling proactive decision-making and improved circuit design. These technologies have shifted crushing from a reactive process to a predictive, data-driven discipline, improving uptime, reducing energy consumption, and enhancing product size consistency.

Energy efficiency has become a central focus in modern crushing plant design, driven by rising power costs and sustainability objectives. Contemporary crushers incorporate optimized chamber geometries that reduce idle power draw and improve material flow. Variable speed drives allow equipment to adjust operating speed based on ore hardness and feed conditions, minimizing unnecessary energy use. Advanced liner profiles maintain optimal nip angles and reduce recirculating loads, while HPGRs continue to demonstrate significant reductions in specific energy consumption compared to conventional milling. Intelligent load management systems ensure that crushers operate under choke-fed conditions, maximizing throughput and minimizing energy per tonne of material processed. Hybrid and fully electric drive systems further reduce mechanical losses and contribute to lower greenhouse gas emissions.

Together, these developments illustrate a clear trajectory toward more efficient, automated, and environmentally responsible crushing systems. From the rudimentary manual methods of ancient miners to today's sensor-rich, AI-optimized comminution circuits, the evolution of crushing technology reflects the mining industry's ongoing pursuit of higher productivity, improved mineral recovery, and reduced operational costs. As ore grades continue to decline and sustainability pressures intensify, the integration of advanced automation, energy-efficient

MMD – Sizers were originally designed for Underground designs, and intelligent monitoring will remain central to the future of crushing in modern mining operations.

MOBILE AND MODULAR CRUSHING PLANTS AND THE RISE OF ECO-EFFICIENT COMMINUTION SOLUTIONS

The increasing complexity of ore bodies, the need for operational flexibility, and the global push toward sustainable mining practices have driven significant innovation in the design and deployment of crushing systems. Among the most transformative developments in recent decades has been the adoption of mobile and modular crushing plants. These systems offer a level of adaptability and efficiency that traditional fixed installations cannot match, while also aligning with the industry's growing emphasis on reducing environmental impact. Their evolution reflects a broader shift toward agile, energy-efficient, and low-emission comminution strategies across modern mining operations.

Mobile crushing plants emerged as a response to the logistical and economic challenges associated with transporting large volumes of run-of-mine material over long distances. By positioning the crusher closer to the working face, mines can significantly reduce haulage requirements, fuel consumption, and associated greenhouse gas emissions. Mobile units – whether track-mounted, wheel-mounted, or semi-mobile – are engineered to maintain high throughput while offering rapid relocation as the pit advances. This mobility reduces the need for extensive civil works and permanent infrastructure, enabling mines to adapt quickly to changing geological conditions. In large open-pit operations, semi-mobile crushing stations are often integrated with conveyor systems, creating a continuous material handling flow that further reduces reliance on diesel-powered truck fleets.

Modular crushing plants extend this flexibility by providing pre-engineered, containerized or skid-mounted units that can be assembled, commissioned, and disassembled with minimal site preparation. These plants are particularly advantageous for remote or short-life projects where the capital cost and construction time of a fixed installation would be impractical. Modular systems allow operators to scale capacity up or down by adding or removing modules, ensuring that the crushing circuit remains aligned with production requirements. Their standardized design also simplifies maintenance, spare parts management, and equipment relocation between sites. As a result, modular plants have become a preferred solution for junior miners, contractors, and operations seeking rapid deployment with reduced environmental disturbance.

The rise of mobile and modular crushing technologies coincides with a broader industry movement toward eco-friendly comminution solutions. Energy consumption in crushing and grinding remains one of the largest contributors to a mine's carbon footprint, prompting manufacturers and operators to pursue more efficient designs. Modern crushers incorporate optimised chamber geometries, variable speed drives, and intelligent control systems that minimise idle power draw and ensure consistent choke-fed operation. These improvements not only reduce specific energy consumption but also enhance throughput and product size distribution.

In parallel, the integration of renewable energy sources into crushing operations is becoming increasingly viable. Solar-powered auxiliary systems, hybrid electric drives, and fully electric crushing units are now available, reducing dependence on diesel and lowering emissions. Electrification also enables the use of regenerative braking and energy recovery systems in conveyors and mobile equipment, further improving overall energy efficiency. For remote sites, modular renewable energy packages can be paired with modular crushing plants, creating low-emission, self-contained processing hubs.

DUST SUPPRESSION AND NOISE REDUCTION

Dust suppression and noise reduction have become central priorities in the design and operation of modern crushing plants, reflecting both environmental expectations and the

MMD surge loader


Dust suppression images

need to safeguard worker health. As mobile units operate closer to communities, haul roads, and active work areas, the industry has invested heavily in technologies that minimise airborne particulates and reduce harmful noise exposure. These advancements not only improve regulatory compliance but also contribute to safer, more efficient, and more sustainable crushing operations.

Dust control has evolved far beyond simple water spraying. Today's mobile crushing plants often incorporate enclosed conveyors, integrated water-misting systems, and foam-based suppression technologies that target dust at its source. Enclosed transfer points and sealed conveyor covers prevent fine particles from escaping into the atmosphere, while misting systems atomise water into ultra-fine droplets that bind effectively with airborne dust. Foam-based systems offer an additional advantage by reducing water consumption – an increasingly important consideration in arid mining regions. Together, these technologies significantly reduce particulate emissions, improving air quality for workers and nearby communities. The growing use of recycled materials, such as reclaimed asphalt and construction waste, further supports dust-control efforts by reducing the need for fresh aggregate extraction and lowering the environmental footprint of crushing operations.

Noise reduction has advanced just as rapidly. Rock crushing plants generate high decibel levels from crushers, vibrating screens, conveyors, and diesel-powered equipment. Prolonged exposure to noise above 85 dB can cause permanent hearing damage, making noise mitigation essential for worker safety and operational compliance. Traditional noise-control methods – such as concrete barriers or heavy enclosures – are often impractical for mobile or elevated installations. In response, the industry has adopted lightweight, portable acoustic barriers that offer a flexible and highly effective alternative.

Modern echo barriers, designed from high-performance acoustic materials, can be deployed quickly around control cabins, operator stations, and high-noise equipment. Their modular design allows them to be configured to suit changing plant layouts, making them ideal for mobile and contract crushing operations. Unlike rigid structures, these barriers can be safely installed at height, enabling noise protection for elevated control rooms, gantry walkways, and maintenance platforms. By absorbing and blocking sound waves, they can reduce noise levels by 10–30 dB depending on placement and configuration. Their durability and weather resistance make them well suited to the harsh, dusty environments typical of quarrying and mining operations.

The integration of these dust and noise mitigation technologies has transformed the environmental performance of mobile crushing plants. Effective dust suppression improves visibility, reduces equipment wear, and enhances air quality, while advanced acoustic barriers protect workers from harmful noise exposure and help operators meet increasingly stringent regulatory standards. Together, these innovations support a safer, cleaner, and more sustainable approach to mobile crushing – one that aligns with modern expectations for environmental stewardship and operational excellence.

Automation and digitalisation further enhance the eco-efficiency of mobile and modular crushing systems. Real-time monitoring of power draw, feed characteristics, and equipment condition allows operators to optimise performance and detect inefficiencies before they escalate. Machine-learning algorithms can adjust crusher settings to match ore hardness variations, ensuring that energy is used as effectively as possible. Predictive maintenance reduces unplanned downtime and extends component life, minimising waste and resource consumption.

Together, these developments illustrate how mobile and modular crushing plants have evolved from niche solutions into central components of modern, sustainable mining operations. Their inherent flexibility, reduced infrastructure requirements, and compatibility with low-emission technologies make them well suited to the industry's current challenges. As mines continue to pursue lower carbon footprints, improved energy efficiency, and greater operational agility, mobile and modular crushing systems – supported by advanced automation and eco-friendly engineering – will play an increasingly important role in shaping the future of comminution.

CHALLENGES FACING MODERN CRUSHING PLANTS AND FUTURE TRENDS IN MINING CRUSHING TECHNOLOGY

Crushing plants today are working under more pressure than ever. Mines are pushing for higher production, ore bodies are becoming harder and more unpredictable, and environmental rules continue to tighten. At the same time, everyone is expected to run safer, cleaner, and more efficient operations. As grades drop and deposits become more mixed, the way a crushing circuit performs can make or break the economics of an entire site. Modern plants must juggle throughput, energy use, equipment reliability, and sustainability in ways that older operations never had to consider. These growing demands are driving major changes in how crushing technology is designed, operated, and maintained across the mining industry.

One of the most significant challenges is the variability of ore hardness and fragmentation. As mines progress deeper or expand laterally, the geological conditions often change, leading to fluctuations in feed size distribution, abrasiveness, and competency. These variations can destabilise crusher performance, reduce throughput, and increase wear rates. Traditional control systems struggle to respond quickly enough to such changes, resulting in suboptimal operation and higher energy consumption. The need for real-time adaptation has become more pronounced as plants push toward higher utilisation rates and tighter process control.

Energy consumption remains another critical challenge. Comminution is widely recognised as one of the most energy-intensive stages in mineral processing, often accounting for a substantial portion of a mine's total power usage. As electricity costs rise and carbon-reduction targets become more stringent, operators face increasing pressure to reduce specific energy consumption without compromising production. Many existing crushing plants rely on legacy equipment that was not designed with modern energy-efficiency standards in mind, making retrofitting or upgrading essential but often costly.

Equipment wear and maintenance also pose ongoing difficulties. Crushers operate under high mechanical loads and abrasive conditions, leading to frequent liner changes, component fatigue, and unplanned downtime. In remote or harsh environments, maintenance logistics can become a major bottleneck. The challenge is not only to extend equipment life but also to predict failures before they occur, ensuring that maintenance is planned rather than reactive. This is particularly important as plants move toward continuous operation models with minimal tolerance for stoppages.

Environmental and regulatory pressures add another layer of complexity. Dust emissions, noise, and vibration must be controlled to meet community and regulatory expectations. Water availability for dust suppression is increasingly constrained in arid regions, forcing plants to adopt alternative technologies. Additionally, the footprint of crushing installations must be minimised, especially in environmentally sensitive areas or operations with short mine lives. These constraints require innovative plant layouts, compact equipment designs, and more efficient material handling systems.

Despite these challenges, the future of crushing technology is marked by promising trends that aim to transform comminution into a more efficient, intelligent, and sustainable process. One of the most influential trends is the integration of advanced automation and artificial intelligence. Machine-learning algorithms are increasingly capable of analysing real-time sensor data to adjust crusher settings, predict wear patterns, and optimise feed conditions. These systems enable crushers to respond dynamically to ore variability, maintaining stable operation and reducing energy waste. Digital twins – virtual replicas of crushing circuits – are becoming valuable tools for simulation, design optimisation, and predictive maintenance planning.

Another major trend is the continued development of energy-efficient comminution technologies. High-pressure grinding rolls (HPGR) have already demonstrated significant reductions in energy consumption compared to traditional SAG milling, and ongoing improvements in roll design, wear protection, and control systems are expanding their applicability. Innovations in cone crusher geometry, variable speed drives, and hybrid electric power systems are further reducing the energy footprint of crushing circuits. The industry is also exploring novel breakage mechanisms, such as microwave-assisted comminution and high-voltage pulse fragmentation, which aim to weaken ore before mechanical crushing, thereby lowering energy requirements.

ADVANCED TECHNOLOGIES TRANSFORMING CRUSHING SYSTEMS IN THE MINING INDUSTRY

The mining industry is undergoing a profound technological transformation, driven by the need for higher productivity, improved energy efficiency, and reduced environmental impact. Crushing, as the first major step in the comminution process, has become a focal point for innovation. Modern operations increasingly rely on artificial intelligence, additive manufacturing, advanced materials engineering, and autonomous systems to enhance the performance, reliability, and sustainability of crushing circuits. These technologies are reshaping the design, operation, and maintenance of crushers, marking a significant departure from traditional mechanical approaches.

Artificial intelligence and machine learning have become central to optimising crushing performance. Historically, crusher control relied on fixed setpoints and operator experience, which often resulted in suboptimal operation when ore characteristics fluctuated. Machine-learning algorithms now process real-time data from sensors measuring power draw, vibration, feed size distribution, liner wear, and

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throughput. These models learn the complex relationships between operating parameters and performance outcomes, enabling dynamic adjustment of crusher settings. AI-driven control systems can maintain choke-fed conditions, prevent overload events, and stabilise the entire comminution circuit. Predictive maintenance is another major application: by analysing historical and live data, machine-learning models can forecast component failures, allowing maintenance teams to intervene before breakdowns occur. This reduces unplanned downtime, extends equipment life, and improves overall plant availability.

Alongside digital optimisation, the mining industry is increasingly adopting 3D printing – also known as additive manufacturing – for crusher components. Traditional manufacturing of wear parts such as mantles, concaves, and liners involves long lead times, complex supply chains, and significant material waste. Additive manufacturing allows for rapid production of customised components with optimised geometries that would be difficult or impossible to achieve using conventional casting or machining. For example, internal lattice structures can be incorporated to reduce weight without compromising strength, while surface textures can be engineered to improve material flow within the crushing chamber. The ability to print replacement parts on-site or near-site reduces inventory requirements and shortens maintenance cycles, particularly in remote mining regions where logistics can be a major constraint. As metal additive manufacturing continues to advance, the potential for producing high-performance, wear-resistant crusher components will expand further.

Materials science has also played a critical role in advancing crusher performance. Wear-resistant materials are essential in crushing applications due to the abrasive nature of ore and the high mechanical stresses involved. Traditional manganese steel remains widely used, but modern operations increasingly rely on advanced alloys, ceramic-metal composites, and carbide-reinforced materials. These materials offer superior hardness, toughness, and resistance to impact and abrasion. Recent developments include nano-structured coatings, tungsten carbide overlays, and hybrid composite liners that significantly extend service life. Longer-lasting wear components reduce the frequency of shutdowns, lower maintenance costs, and improve crusher availability. In addition, improved wear resistance contributes to more stable crusher performance over the life of the liners, enhancing product size consistency and energy efficiency.

The integration of autonomous crushing systems represents another major step forward in mining technology. Autonomous crushers operate with minimal human intervention, relying on advanced sensors, automated control algorithms, and remote monitoring platforms. These systems continuously adjust operational parameters in response to changing feed conditions, ensuring optimal performance without the need for constant operator oversight. Autonomous crushing is particularly valuable in large-scale operations where consistent throughput and reliability are essential. When combined with autonomous haulage and in-pit crushing and conveying (IPCC) systems, autonomous crushers form part of a fully integrated, automated material handling chain. This reduces reliance on diesel-powered truck fleets, lowers emissions, and enhances overall process stability. Remote operation also improves safety by removing personnel from hazardous areas around the crusher.

Together, these technologies illustrate the rapid evolution of crushing systems in the mining industry. AI and machine learning provide the intelligence needed to optimise performance in real time. Additive manufacturing enables rapid, flexible production of high-performance components. Advanced wear-resistant materials extend equipment life and reduce operational costs. Autonomous crushing systems integrate these innovations into a cohesive, self-optimising process. As ore grades continue to decline and sustainability pressures intensify, the adoption of these advanced technologies will become increasingly essential. The future of crushing lies in systems that are not only mechanically robust but also digitally intelligent, materially advanced, and operationally autonomous – capable of delivering higher productivity with lower energy consumption and reduced environmental impact.

CONCLUSION

The development of crushing technology mirrors the wider transformation of the mining industry. What began with simple manual rock-breaking has evolved into highly engineered comminution systems designed for efficiency, improved mineral liberation, and lower operating costs. The shift from early hammering and fire-setting to steam-powered and later electrically driven crushers laid the groundwork for modern large-scale operations, while twentieth-century advances such as hydraulic systems, improved liner materials, and HPGRs further boosted performance and energy efficiency.

Today's crushing plants face growing challenges as ore bodies become deeper, harder, and more variable. Energy use remains a major constraint, and environmental pressures around dust, noise, emissions, and land disturbance demand cleaner, more compact plant designs. At the same time, operators must maintain high equipment reliability and safety in increasingly demanding conditions.

To meet these pressures, the industry is adopting advanced technologies that are reshaping the future of comminution. AI and machine-learning systems now enable real-time optimisation and predictive maintenance, turning crushing into a more stable and self-correcting process. Additive manufacturing allows rapid production of customised, high-performance components, while new wear-resistant materials extend equipment life and reduce downtime. Autonomous crushing systems, supported by sensors and remote operation, offer safer, more continuous, and more energy-efficient material handling.

Sustainability is now central to crushing plant design. Energy-efficient equipment, electrified drives, renewable-powered systems, and improved dust and noise control all help reduce environmental impact. Mobile and modular plants further support low-impact mining by reducing civil works and haulage requirements.

Overall, the future of crushing lies in smarter, more adaptable, and more environmentally responsible systems. As ore grades decline and sustainability expectations rise, these innovations will be essential for maintaining productivity, reducing energy consumption, and ensuring the long-term competitiveness of modern mining.

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