Embedding sustainability in global mining practices

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Introduction

As the world's population is projected to reach 10 billion people over the next 50 years, demand for electronic devices, electric vehicles, solar panels and sustainable buildings is expected to increase, requiring more copper, lithium, nickel, cobalt and rare earth elements. These minerals are essential to a low-carbon future.

Achieving a net-zero target by 2050 requires the greening of high-emission industries like steel production, which accounts for approximately seven to nine per cent of global CO_2 emissions. The challenge lies in increasing the production of essential metals while minimising environmental impact and maintaining economic viability.

One approach is optimising mining operations using mathematical algorithms powered by advances in computer technology. Another is creating a circular economy for critical minerals and metals, allowing for less mining and more recycling into batteries and other key green technologies. Electrification represents another crucial shift, as companies progressively replace diesel-powered equipment with electric alternatives to reduce environmental impact.

Cutting across all of these innovations is the need for energy efficient machinery that uses less power and water, and for greater automation of mine operations. Australian mining companies are already recognised as world leaders in autonomous vehicle deployment, particularly in the Western Australia's Pilbara region, which has removed humans from hazardous situations and increased efficiency.

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Finally, artificial intelligence (AI) and data analytics are emerging as transformative forces, with mining's data-rich environment – from exploration through to processing and metal production – providing substantial opportunities for AI applications to deliver critical information to decision-makers in real time.

Further investment is required by mining companies and government to accelerate these innovations, moving from the laboratory to the mine site. In doing so, Australia could enhance and strengthen its traditional role as a raw material exporter and become a world leader in sustainable mining.

Innovating sustainable mineral processing

Current mineral processing techniques are energy and water intensive. In the case of copper mining, grinding ore into a fine powder is often necessary to separate valuable minerals from gangue (waste rock). This process accounts for most of a mine's energy and water consumption. It also produces a liquid slurry, which is stored in large and potentially hazardous tailings dams. When these dams fail, they can cause catastrophic environmental damage and loss of life.

The solutions for these challenges require a paradigm shift. University of Melbourne researchers, led by Professor George Franks and his colleagues in the Australian Research Council Centre of Excellence for Enabling Eco-efficient Beneficiation of Minerals, are developing techniques to reduce energy, water and waste in mineral processing and mitigate environmental risks associated with traditional methods.

The most effective way to reduce a mine's energy and water use is to remove waste rock at the earliest possible stage. Instead of grinding all the ore into a fine flour-like powder (about 100 microns), researchers are developing methods to separate the waste from the valuable ore when it is about 10 times bigger, or the size of sand particles (less than one millimetre).

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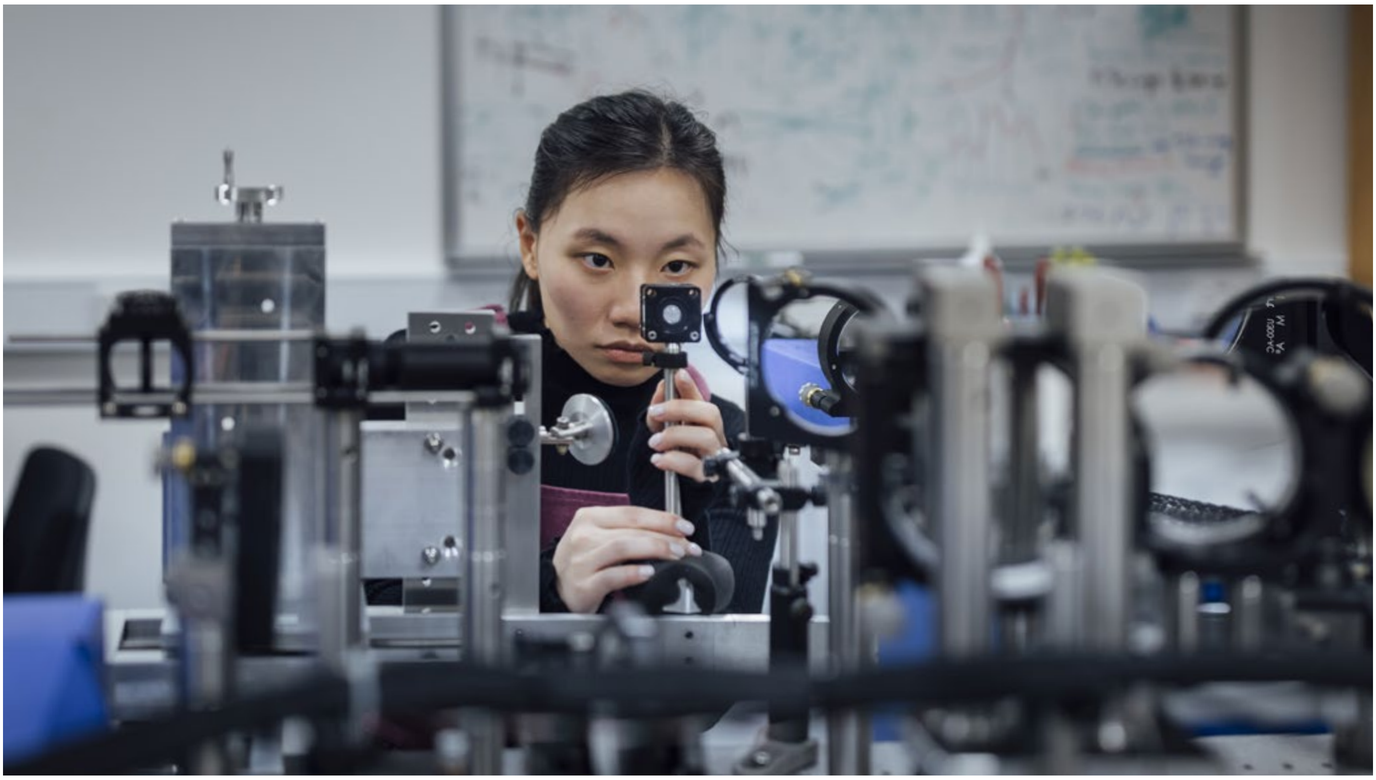
Rejecting waste before the energy-intensive grinding process reduces energy consumption by up to ten times and has the potential to cut water consumption by half. Researchers are designing new equipment and chemical reagents to try to separate coarse particles more efficiently.

More value from fine particles



The grinding process can cause a substantial loss of valuable minerals from the ore because the finest particles are difficult to recover using conventional methods. For some mines, up to 40 per cent of their target mineral ends up in the waste stream.

The University of Melbourne team is investigating “flocculation flotation” as a method to recover more minerals. The researchers are making significant progress using new equipment that separates particles at larger sizes, along with chemical reagents that enable these separations.

They add a specialised polymer to the fine mineral solution that acts as a glue, causing the tiny mineral particles (10 microns) to stick together, or aggregate, into larger clumps (100 microns). These aggregated clumps are then large enough to be recovered through standard flotation processes.

This technology provides two benefits:

- It significantly increases the recovery of valuable minerals from the same amount of ore, so less rock needs to be mined to meet demand.
- Mines can reprocess old tailings that still contain valuable minerals. By re-extracting these lost minerals, companies may get more value from existing waste and reduce the environmental footprint of new mining operations.

Meanwhile, to eliminate the need for risky tailings dams, researchers are also developing a new “de-watering” technology using high-pressure rollers. This equipment replaces traditional, space-consuming thickeners. It squeezes the water out of the tailings, producing a solid cake that can be safely dry stacked. This dry-stacking process is more stable than storing wet slurry and drastically reduces the risk of environmental disasters.

Shifting to sustainable mineral processing

An additional challenge for researchers is the mineral processing industry's historical reluctance to adopt new technologies. Laboratory innovations can take up 10 to 20 years to become standard practice in commercial mining operations.

Beyond technical feasibility, mining companies also require robust economic analysis to understand exactly when and where a new technology will provide the greatest benefit. This ensures that innovations are not only environmentally sound but also economically competitive.

Mines will need to move away from using a series of complex, sequential processing stages towards more efficient, single-stage separation technologies. Simplifying processes will reduce costs, improve efficiency and lower the overall environmental footprint of mining operations.

Mining companies are increasingly turning to mathematical models based on large data sets to optimise their operations as they design the future of their businesses. This modelling helps them with mine planning from the short term (days) to the long term (years).

For example, they might consider how much mineral to extract and process as accessible deposits decline, the investment timeframe and capital requirements, and the best ways to meet sustainability targets. Advances in sensor technology also enable precise mineral composition analysis, generating extensive data that requires sophisticated analytical approaches.

To assist companies in tackling these challenges, researchers at the University of Melbourne, led by Dr Michelle Blom, are developing mathematical models to inform the creation of precise operational plans and ensure new investment delivers optimal value and outcomes. These models break down large-scale problems to generate solutions more quickly.

By enabling more efficient and precise planning, these algorithms can reduce waste and improve resource extraction by narrowing the required time, effort, equipment and capital investment. Integrating sustainability goals into the core planning process also helps companies meet environmental targets and build a more responsible and resilient industry for the future.

For decades, mining companies relied on simplified planning models that often ignored operational and market risks. Today's market volatility and demand for greater accuracy have generated complex computational problems that exceed the capabilities of traditional software.

Considering uncertainty

Dr Blom and her team often use a technique called stochastic optimisation, which takes uncertain or random factors into account. The uncertain factors could include variable ore grade quality, future commodity prices and potential government regulatory changes. Stochastic optimisation helps companies develop robust plans that anticipate various future scenarios, reducing risk and enabling better-informed decisions.

The researchers help mining companies by breaking down large, complex problems into smaller sub-problems that can be solved more quickly whilst still achieving effective solutions.

In the Pilbara, for example, different mine sites work together to produce various blended products. The researchers must assess entire networks of mines connected to ports and railways, rather than planning for individual sites, whilst accounting for uncertainty throughout the system.

Dr Blom's team recently completed an optimisation project for Rio Tinto, a global company with 60,000 employees and operations in 35 countries. The researchers used a technique called Large Neighbourhood Search. This technique enabled them to systematically explore a vast number of solutions to find a near-optimal outcome by iteratively moving from good solutions to even better ones.

Beyond efficiency, mathematical optimisation is also key to integrating sustainability into mining operations. While researchers have long considered mine closure and rehabilitation, they are now focusing on a more holistic approach that includes emissions reduction and responsible resource management. This is driven by both regulatory pressures and a broader industry commitment to long-term sustainability over the next five to 10 years.

"Direct block scheduling" is another key industry trend, focusing on the most detailed level of the ore body rather than larger, aggregated sections. While this poses a computational challenge, it leads to a higher degree of precision and greater value from the mineral deposit.

Partnerships between industry and academia are crucial for this work, bringing together deep operational knowledge with cutting-edge mathematical and algorithmic expertise to solve today's complex problems and build a more responsible and resilient mining industry for the future.

There is also a strong push for multi-horizon planning to connect a company's long-term strategic planning with its day-to-day operations. This ensures that short-term decisions don't compromise long-term value, creating a more holistic and efficient planning framework.

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Pioneering a circular economy for critical minerals

The green recycling of lithium-ion batteries in Australia presents a significant opportunity to create a circular economy, enhancing supply chain resilience and develop promising economic opportunities.

While Australia is rich in critical minerals, the country remains heavily reliant on imported refined materials. Less than 10 per cent of our lithium-ion batteries are recycled domestically. The few batteries that are processed are shredded into a black mass to extract valuable metals including lithium, copper, manganese, cobalt and nickel.

Typically, the black mass is exported overseas for refining, so Australia doesn't get the full economic benefit or achieve a closed-loop process that directly reuses recycled materials to create new batteries.

Most of Australia's lithium-ion batteries end up in landfill, leading to environmental pollution and the loss of valuable resources. The limited domestic processing capacity also means that large volumes of batteries are stored in warehouses and scrap yards, creating a potential fire risk and the possibility of environmental contamination.

However, existing recycling methods have significant drawbacks. Pyrometallurgy is an energy-intensive process that requires high temperatures (between 1000°C and 2000°C) that generates substantial greenhouse gases. This process often fails to recover valuable lithium, which frequently gets lost in tailings. Hydrometallurgy often relies on hazardous chemicals such as strong acids and bases, which produce large volumes of toxic wastewater and pose risks to both the environment and human health.

University of Melbourne researchers are developing greener, more efficient recycling methods that could fundamentally reshape the sustainable resources industry and address these challenges to create a circular economy that is vital for our future prosperity and environmental stewardship.

Pioneers for a greener solution

Dr Helena Wang's Renewable Resources and Sustainability Group is replacing energy-intensive pyrometallurgy with rapid heating methods, such as microwave heating and flash heating. These techniques, which achieve high temperatures in seconds, are far more energy efficient and, crucially, enable selective recovery of valuable metals such as lithium, which traditional pyro-methods fail to capture.

The team is also exploring green solvent hydrometallurgy using deep eutectic solvents (DES). Unlike hazardous chemicals, DES is composed of safe, readily available and inexpensive components such as choline chloride and urea (a common fertiliser). These components efficiently leach minerals without producing harmful wastewater. This process can be combined with microwave heating to ensure that extracting minerals is more efficient.

The researchers' most promising innovation is direct recycling, which regenerates degraded material from spent batteries into new, battery-ready material without breaking it down into constituent ions. This process significantly reduces the number of steps, making it more economically viable and environmentally sound.

With an unprecedented surge in demand for batteries driven by electric vehicles and large-scale renewable energy storage systems, battery recycling is becoming as critical as battery manufacturing itself. Within the next five to 10 years, a massive wave of retired batteries is expected to enter the market. How we manage this influx will define our environmental and economic future.

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If handled properly, battery recycling represents a vast untapped resource for Australia, often referred to as urban mining. If recycling does not keep pace with demand, it could lead to environmental harm and the loss of invaluable materials.

Countries such as South Korea, despite its limited mineral resources, have commercialised advanced recycling technologies and are already integrating recycling directly into battery manufacturing.

By investing in innovative recycling methods and building the necessary domestic infrastructure, Australia could transition from merely a raw material exporter to a key player in the entire critical mineral value chain. This would not only contribute to Australia's economic future but also position the country as leaders in sustainable technology and environmental stewardship.

Future electronics designers could embed circular economy principles directly into their devices, replacing built-in obsolescence with sustainability by design.

Conclusion

Australia's mining industry stands at a critical juncture, uniquely positioned with reserves of critical minerals essential for the anticipated global population growth and required transition to a low-carbon economy. By strategically investing in and swiftly commercialising innovations – from more integrated, single-stage processing to advanced domestic recycling infrastructure – Australia has the potential to move from its traditional role as a raw material exporter.

This positions the University as a key partner for advancing sustainable mining practices globally.

An integrated approach that prioritises efficiency, responsibility, sustainable operations and circularity is essential for securing the primary resources industry's future and establishing Australia as the definitive global leader in sustainable mining.

The University of Melbourne's enduring success in corporate engagement provides a strong foundation, but the true potential for accelerating innovation lies in developing deeper and more integrated industry partnerships.

The University maintains strong collaborative relationships with the resources industry, both domestically and internationally, offering significant research expertise across mining, mineral processing, AI and electrification. This positions the University as a key partner for advancing sustainable mining practices globally.

Overcoming the mining sector's inherent risk aversion to innovation also requires more than just exceptional research. Successful rapid adoption relies on seamlessly merging the University's scientific expertise with the industry's operational knowledge and capital.

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