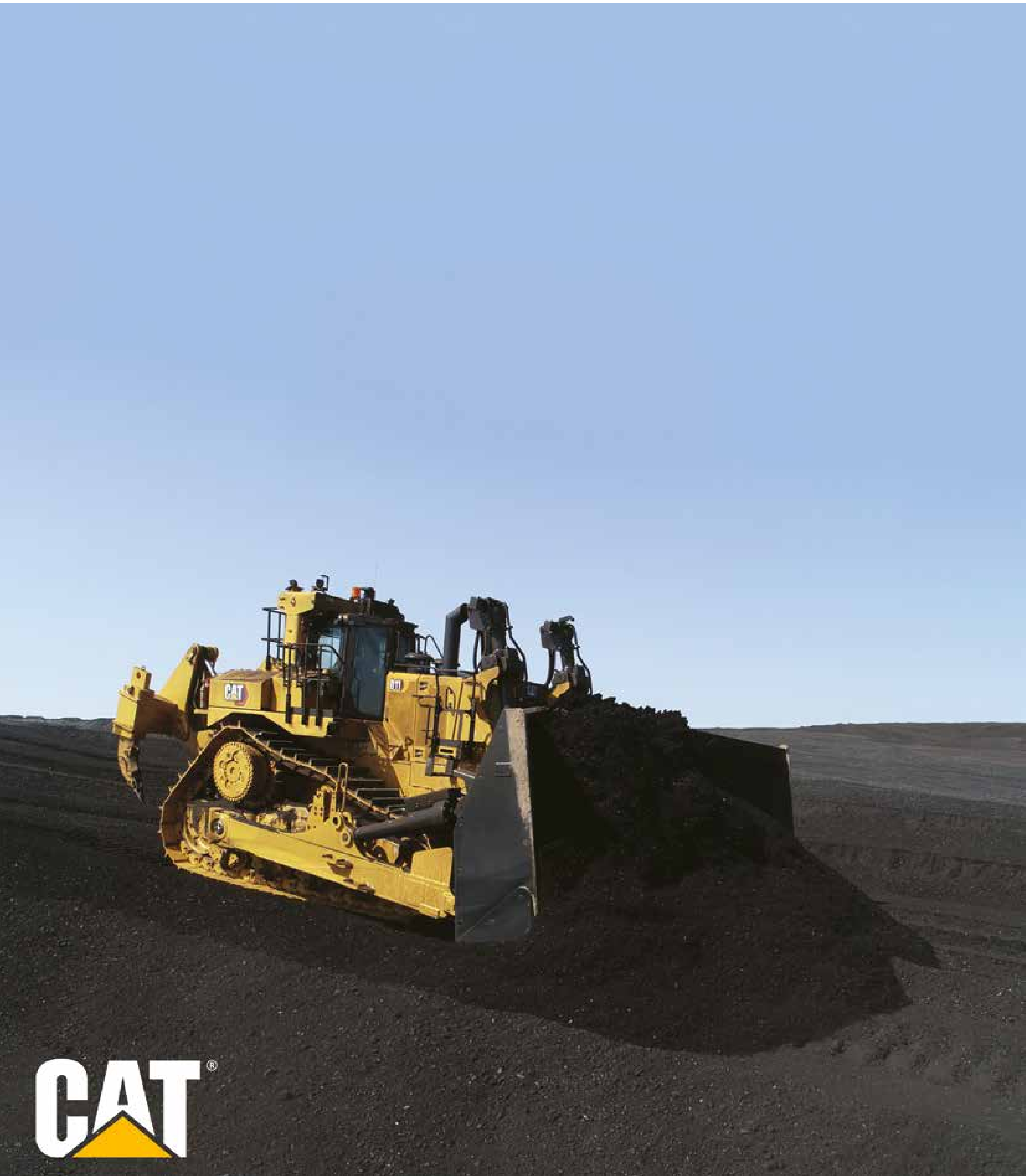
COAL INTERNATIONAL

Volume 273 · Number 5

September-October 2025



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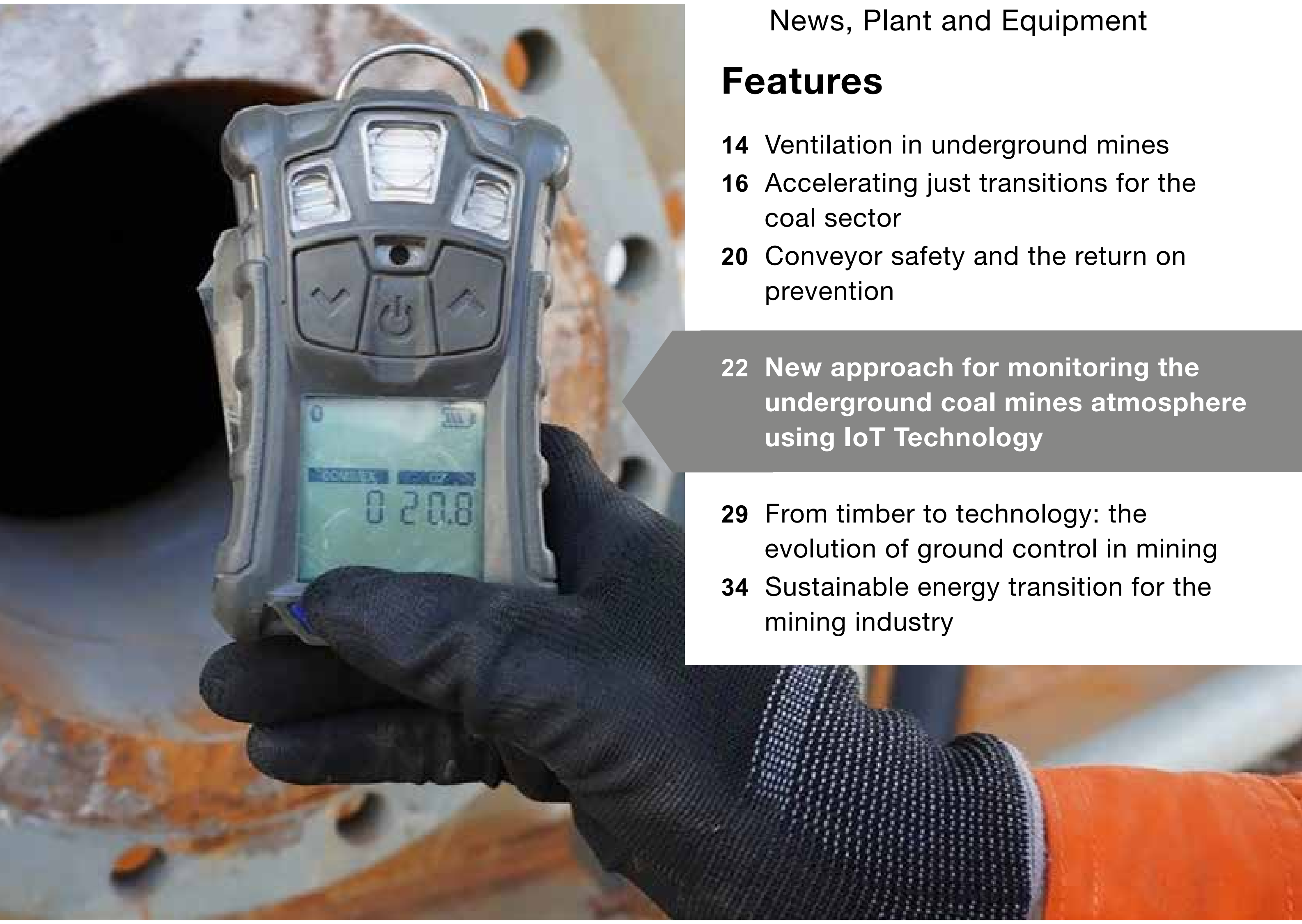


The Cat® D11 on the cover features several updates that improve durability, reliability and performance over multiple lifecycles. Built to be rebuilt, the D11 is designed to deliver the lowest possible total cost of ownership.

Managing Director and Publisher: Trevor Barratt

International Sales:
Gordon Barratt +44 1909 474258 gordon.barratt@tradelinkpub.com

Graphic Designer: Sarah Beale sarah@g-s-g.co.uk

Published by: Tradelink Publications Ltd.
16 Boscombe Road, Gateford, Worksop, Nottinghamshire S81 7SB

Tel: +44 (0)1777 871007
Fax: +44 (0)1777 872271
E-mail: admin@mqworld.com
Web: www.mqworld.com

How Komatsu longwall technology is redefining risk in Australian coal mines

As Australian operations continue to push deeper into complex geological seams, the industry's appetite for safer, smarter technology has never been greater.

Enter Komatsu's next-generation longwall system – a fully integrated, automation-ready solution that's transforming safety outcomes across Australia's underground coal sector.

Australia's underground coal mines, particularly in New South Wales and Queensland, operate under some of the world's strictest safety frameworks. From the WHS (Mines) Regulations to compliance with Longwall Automation Steering Committee standards, operators are expected to not only maintain productivity but drive toward zero harm in the process.

For Komatsu, this is not a constraint; it's a design principle.

"We've engineered every component of our longwall technology to reduce manual interaction, enhance operational visibility, and anticipate failures before they happen," Komatsu engineering manager control and automation Shane Cooling told Safe to Work. "In Australia, that's non-negotiable."

The cornerstone of Komatsu's safety-first approach is the Longwall Automation Package, a suite of tools that removes the need for constant human presence at the longwall face. Whether its advancing powered roof supports or managing horizon control on the shearer, Longwall Automation Package automates some of the most hazardous tasks in the section.

Paired with Faceboss RS20s and Faceboss 2.0 controls and the Joy Smart Solutions analytics, this system doesn't just respond to conditions, it predicts them.

Personnel can monitor operations remotely, well away from the face, with real-time alerts for hydraulic loads, convergence data, and equipment performance.

Field-Proven in the Hunter Valley

A standout case study comes from Mandalong Mine (Centennial Coal), where Komatsu's RS20s PRS and full automation suite were deployed in a low-seam panel (<1.6m). The results were hard to ignore, with an average of more than 95% across all shifts using surface remote automation, and an estimated eight% productivity increase through consistent cutting and fewer stoppages.

According to site management, the automation enabled a shift in workforce deployment, moving personnel out of the highest-risk areas without compromising coal recovery.

In addition to automation, Komatsu has a Personal Proximity Detection System, a proven technology in NSW and Queensland coal mines. These systems create safety zones around the moving machinery and can automatically halt powered roof supports and the shearer when people breach defined boundaries.

Combined with predictive maintenance tools and remote diagnostics, the full longwall package supports a "control-first approach", engineered safeguards that reduce reliance on procedural workarounds or reactive interventions.

While safety is the priority, operators aren't ignoring the commercial upside. Komatsu reports that mines implementing full Longwall Automation Package and JoySmart systems are seeing reduced unplanned downtime, lower injury-related insurance costs, and faster panel development with fewer stoppages.

With payback periods often under two years, Komatsu said the value proposition is hard to dispute.

As automation moves from "nice to have" to "critical path," the company believes its integrated longwall system will become the default for mines aiming to meet safety and production benchmarks.

"Our vision is simple," Cooling said. "Keep miners out of harm's way, give engineers better data, and let the system do the heavy lifting. In Australia, that's the future of longwall mining."

Peabody expects big jump in demand in Trump era

Swelling US demand for electricity has the potential to boost coal consumption as much as 57%, according to mining giant Peabody Energy, in what would be a major shift for an industry that's been waning for years.

With the US seeking to meet skyrocketing demand and the Trump administration pushing to prop up the coal industry, Peabody expects utilities to ramp up output from coal plants that are running well below full speed, the company said in an investor presentation recently. Boosting usage to "historic capacity factors" could lead to more than 250 million tons of additional annual demand in the coming years, it said.

Still, analysts see this forecast as a mathematical maximum that's unlikely to be achieved in the real world.

US coal usage has been steadily declining as utilities shift away from the dirtiest fossil fuel. But President Donald Trump's pro-coal and anti-renewable approach has included blocking a Michigan power plant's plan to shut down this year. Total consumption is expected to be 439-million tons this year, according to the US Energy Information Administration. That's up 6.7% from last year, but well down from its 2007 peak of 1.13-billion tons.

"Peabody sees great untapped potential for existing US coal plants," Mark Spurbeck, CFO for the St. Louis-based company, said by email.

Electricity demand in the US is set to climb 25% through 2030, driven by factories, increasingly electrified homes and especially from the booming buildout of data centers used for artificial intelligence. At the same time, supply-chain constraints have hindered utilities' efforts to add more natural gas plants.

That's spurring increased reliance on underused coal plants, which have significant potential to deliver more power. The US fleet was operating at just 42% last year, according to Peabody, compared to 72% in 2008.

Still, anticipating demand to climb by 250-million tons assumes that coal plants are all ramped up close to 100%, which is unlikely, said Andy Blumenfeld, director of data analytics at McCloskey by Opis.

"That's a really big number," he said. "It's a theoretical maximum, if everything works perfectly. And they don't."

US plans to use emergency powers to stop more closures

The Energy Department has already issued emergency orders to halt the retirement of two fossil fuel-fired plants, and plans to use the same process to keep others operating, said the people, who asked not to be named discussing internal matters.

Although such orders are typically reserved for natural disasters or war, the agency used them to stop the closure of a Michigan coal-fired power plant owned by Consumers Energy and a Pennsylvania oil-and-gas generator owned by Constellation Energy Corp.

"I think this administration's policy is going to be to stop the closure of coal plants," Energy Secretary Chris Wright said during an event held by the New York Times. Shutting down coal-fired power plants "that are working today" would drive up electricity prices, and hinder efforts to reindustrialize the US economy, he said.

Some 8.1 gigawatts of coal-fired power, or about 5% of the total US fleet, is set for retirement in 2025, according to the Energy Information Administration.

The Trump administration has prioritized expanding the use of a coal and argued that the closure of fossil fuel-powered plants threatens the grid amid an AI-driven demand surge. At the same time, the White House has halted wind projects and rolled out policies that disadvantage solar and other renewable energy sources.

The Energy Department and the White House didn't immediately respond to a request for comment.

The moves drew criticism from regulators and environmentalists who said no emergency exists and that such orders would increase consumer electricity costs.

"We're not going to close any coal plants, but we're trying to protect the American consumers to get affordable electricity," Wright said recently. "We want data centers to be able to locate here. We want semiconductor manufacturing to locate here. We want aluminium and steel production to come back and that takes energy."

Coal is rising along with solar in the US power system

Coal and utility-scale solar power each gained market share in the first half of this year, newly released data on US electricity generation show.

Natural gas, while still the market leader, lost some share.

So what's going on?

Meanwhile, the Trump administration's efforts to prevent the closure of old coal plants were too recent to have much of an effect on national data.

The gains for utility-scale solar were predictable, considering the large number of solar projects that are coming online.

From January to June of this year, US power plants generated 2.1 million gigawatt-hours of utility-scale resources, representing a 2.9% increase from the same period in 2024, according to the Energy Information Administration. Here is the mix of resources behind the total:

The increase for coal and decrease for gas can be largely attributed to the prices of each fuel, according to analysts. The rising cost of natural gas has made coal the more affordable option for some power plant owners.

The big movers were natural gas, which lost 2.7 percentage points of market share, and coal, which gained 2 percentage points.

Renewables gained 1.5 percentage points, which was almost entirely attributable to utility-scale solar. Wind and hydropower, the other leading sources of renewable energy, were essentially flat.

The main driver of coal's increase and gas' decrease is that the US benchmark price of natural gas was up substantially in the first half of the year compared to the first half of last year, said Michael Goggin, vice president of Grid Strategies, a consulting firm.

"Plant owners are very sensitive to those price differences in the fuels," he said. "If it's a little bit cheaper to run coal as gas prices get higher, then utilities and other power plant operators are going to do that."

Another important factor is the continuing increase in US electricity demand from data centers and other large users, which was met by an increase in supply.

While an increase of 2.9% may not seem like a lot, it's a pretty big shift following two decades in which there was little change in net generation, with average annual growth of less than 1%.

This projected period of rapid growth for the electric sector is good for just about anybody who owns a power plant. Investors are spending heavily on natural gas power plants, wind, solar and batteries, based on data for plants in develop But they're not building new coal-fired plants. The most recent large coal plant to come online was Sandy Creek Energy Station in Texas in 2013, with summer capacity of 932.6 megawatts. The most recent coal plant of any size was a 17-megawatt system that went online in 2020 at the University of Alaska Fairbanks.

Even with the support of the Trump administration, the country's coal plants are mostly old and expensive to operate.

"There's an inexorable long-term trend that gas and renewables are replacing coal generation," Goggin said.

This recent increase in coal power's market share is not a sign of a bright future for the technology, said Brendan Pierpont, director of electricity modelling for the think tank Energy Innovation.

"Short-run fluctuations aren't stopping the long-run decline," he said, pointing to several factors, including the fact that plants become more expensive to operate as they age.

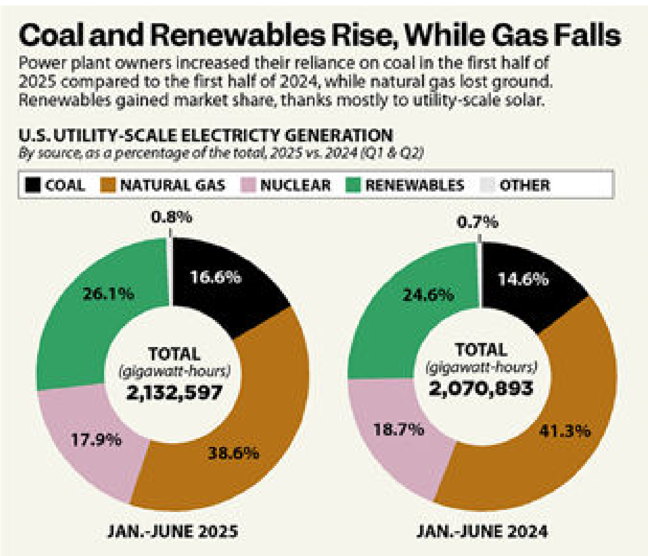
In the meantime, it is interesting to see where coal had the greatest gains this year. Indiana and Michigan are among the states that stand out for having large increases in coal-fired power.

Michigan is home to the J.H. Campbell plant, which was scheduled to close in May but is staying open because of a Trump administration order that says the plant is needed to maintain grid reliability. Michigan utilities were already increasing their use of coal power due to market forces such as gas prices, even before the administration's order.

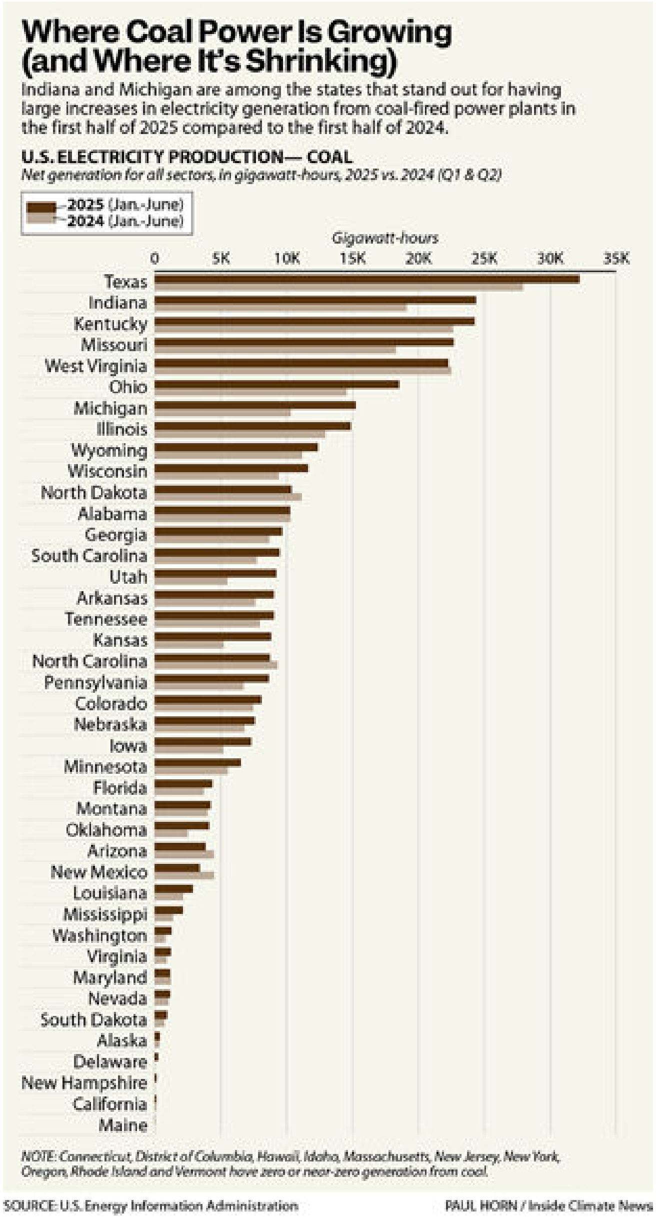
The order had minimal effect on this batch of data, since the plant was only operating in one month, June, when it otherwise would have been closed.

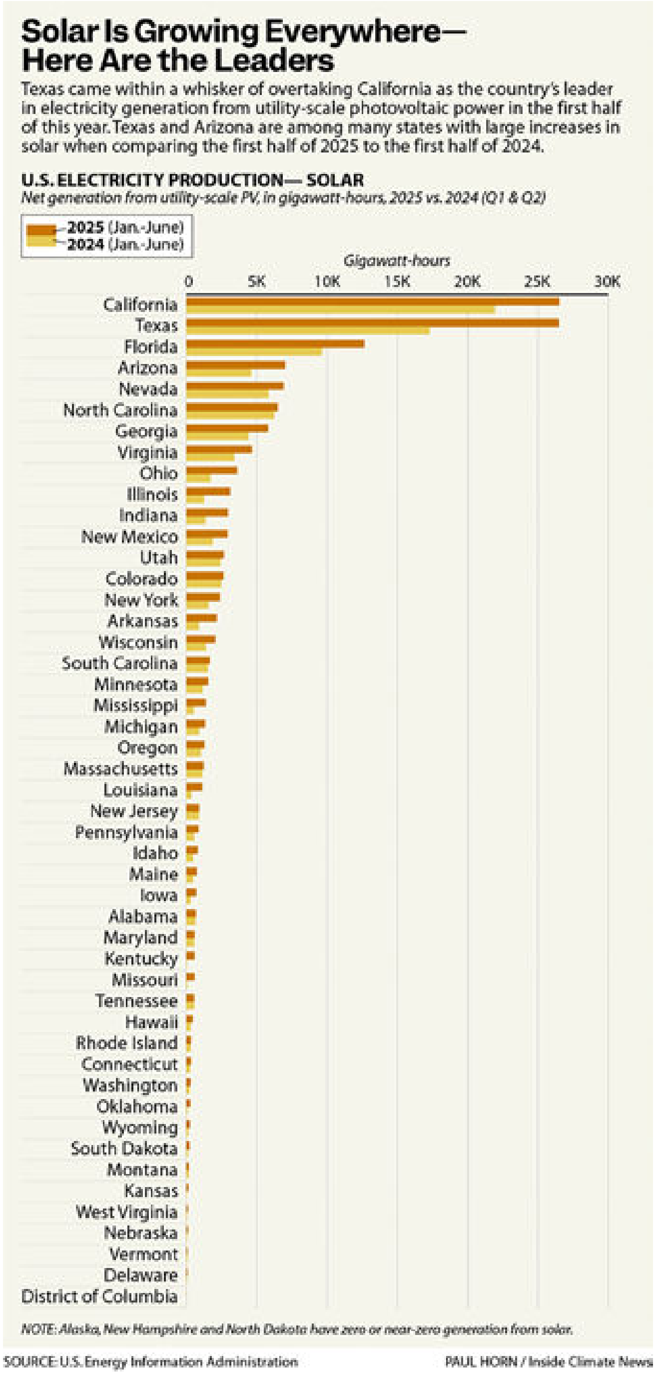
Goggin analysed this order in a report sponsored by environmental advocacy groups. He found that if the administration uses emergency declarations to stop coal plants from closing over the remainder of President Donald Trump's term, the positive effects on reliability would be minimal and the costs to consumers would increase by $3.1 billion to $5.9 billion per year.

Utility-scale solar is rising almost everywhere in the United States. California has long been the leader in generation from utility-scale solar, but Texas has now moved into a virtual tie, with California ahead by less than 0.1%. Texas is on a pace to become the leader, and it may



SOURCE: U.S. Energy Information Administration PAUL HORN / Inside Climate News





clearly have that status within a month or two.

Ohio, Illinois and Indiana stand out for having doubled their electricity generation from utility-scale solar generation in the first half of this year compared to the first half of last year. Those states now rank ninth, 10th and 11th, respectively, in the United States for generation from utility-scale solar.

While I'm focusing on utility-scale solar, small-scale solar has also grown. The Energy Information Administration defines small-scale solar as any project with capacity of 1 megawatt or less, which mainly includes rooftop systems owned by consumers. These systems generated 47,025 gigawatt-hours in the first half of the year, which, for perspective, was about one-third of the generation from utility-scale solar.

It can be challenging to talk about small-scale solar in the context of national totals because these small projects are not utility-scale resources, so they don't have a slice of the donut in the first graphic above.

But rooftop solar and other customer-owned resources are important for the way they reduce demand for power plants on the grid. Each kilowatt-hour a customer generates for themselves is one that a centralized power plant doesn't need to produce.

When asked for big-picture observations about this data, Pierpont noted that the market share for fossil fuels is on a long-term downward trend that has continued this year. That share was 55.9% in the first half of this year (including coal, gas and fuels with tiny shares, such as petroleum liquids), down 0.6 of a percentage point from the first half of last year.

Much of the movement in the last six months was driven by coal trading market share with natural gas, but the long-term trend is the rise of renewables and the decline of fossil fuels, he said.

"Looking forward, solar is a big share of the projects expected to be built in the remainder of this year and next year, and over the long run it will continue to be a low cost way of meeting growing demand that helps protect customers from the volatility in coal and gas costs– so I expect it to continue to eat into market share from coal and gas," he said.

I'll add a caveat: The Trump administration could succeed, at least in the short term, in slowing this long-term trend. But that's more of a blip than a fundamental change in direction

Glencore gets federal go-ahead for Ulan expansion

Glencore's Ulan coal mine has received Federal Government approval to expand its underground mining reach.

The Department of Climate Change, Energy, the Environment and Water gave the green light to the proposed Ulan Coal Modification 6 – Underground Mining Extension plan recently.

This will allow Glencore to "expand underground longwall mining operations and associated infrastructure" at the Ulan Coal Complex, in the central west region of New South Wales.

The expansion is expected to allow Glencore to access an additional 18.8 million tonnes of coal at Ulan, with the licence now extended until 2035.

The approval is subject to a biodiversity management plan, that focuses on protection of a unique bat species and native grasslands.

Glencore will be subject to strict land clearing limits, that restrict clearing to 17.4 hectares (ha) of large-eared pied bat foraging habitat, as well as 5.9ha of white box, yellow box, and Blakely's red gum grassy woodland.

A water management plan is also in place, with Glencore required to publish its monitoring program results at least yearly.

In May, Glencore received approval for the modification

from the NSW Department of Planning, Housing and Infrastructure.

With a comprehensive environmental management system already in place at the mine, the state regulator noted that the potential environmental impacts of the expansion plan could be successfully "avoided, managed and offset".

It attached 13 conditions to its approval, focused around managing biodiversity, greenhouse gas emissions, water usage, and Aboriginal cultural heritage.

US plans lease sales in Alabama, Utah and Montana

The US Department of the Interior said recently it would advance three competitive coal lease sales this fall, offering tracts in Alabama, Montana and Utah as part of the Trump administration's effort to expand domestic energy production.

"Coal has long been the backbone of America's energy and industrial strength," Interior Secretary Doug Burgum said in a statement. "By moving forward with these lease sales, we are creating good-paying jobs, supporting local communities, and securing the resources that keep America strong."

In Alabama, the Bureau of Land Management (BLM) will auction two lease areas spanning about 5 686 ha beneath private lands in Tuscaloosa county. The tracts contain an estimated 53-million tons of recoverable metallurgical coal, a steelmaking input designated as critical under the Energy Act of 2020. The sealed-bid sale is scheduled for September 30 in Falls Church, Virginia.

The BLM also plans a sale in Utah's Emery county, offering the 48.50-ha Little Eccles Tract with an estimated 1.29-million tons of recoverable coal. Canyon Fuel, operator of the Skyline mine, applied for the lease. Sealed bids are due October 1, with the sale taking place that afternoon in Salt Lake City.

In Montana's Big Horn county, the agency will put forward a 510-ha tract containing 167.5-million tons of recoverable coal. Navajo Transitional Energy, operator of the Spring Creek mine, submitted the application. If issued, the lease could extend the mine's life through 2051. The sale will be held October 6 in Billings, Montana, with sealed bids due by October 3.

Each lease remains subject to federal review, including environmental analysis and public comment, and bidders must secure required state and federal permits, including an approved mining plan.

India launches pilot to pair coal plants with battery storage amid solar surge

India will pilot battery storage at coal-fired power plants to soak up surging midday solar and keep thermal capacity ready for the evening peak—without destabilizing the grid.

The move targets a growing bind: solar now forces coal units to back down during the day, yet demand still leans on them after sunset. With a 2030 goal of 500 GW of non-fossil capacity, that tension is only rising.

"At times there are only two choices. Either you shut down the coal plant (during excess solar generation) or lose the thermal capacity in the evening, which we don't want," said Ghanshyam Prasad, chairman of the Central Electricity Authority (CEA), at PowerGen India 2025 in New Delhi. "We are just trying this as an experiment."

To test a way out, the CEA has asked NTPC, India's largest coal generator, to install batteries at select plants with funding support. The idea is simple: charge when renewable output is high and discharge later, letting coal units run more steadily, cut cycling costs and potentially extend asset life.

The scale matters because India's transition is a balancing act. Renewables are accelerating, yet coal remains central to round-the-clock supply. The government plans to add 97 GW of coal capacity by 2035, lifting the fleet to roughly 307 GW even as flexibility and storage ramp up.

But flexibility isn't free. Running coal units at lower loads can speed wear and tear. "If we maintain operations at that level for extended durations, the anticipated lifespan of a plant – usually around 25 years – could be reduced by a third or more," said NTPC director of operations Ravinder Kumar.

Regulation is pushing in the same direction. Coal plants must now operate down to a 55% minimum load and meet specified ramp rates. A 40% target is under consideration, though NTPC has flagged durability risks and is holding its technical minimum at 55% for now.

All of this unfolds against a stark storage shortfall. India has only about 500 MWh of operational batteries, versus a multi-gigawatt need by the early 2030s. Though, around 12.5 GW of projects are under tender, with another 3.3 GW in the pipeline, helped by the Union government's Viability Gap Funding scheme that covers roughly 30% of capital costs.

If the pilot works, coal-plus-batteries could become a practical bridge – squeezing more flexibility from existing thermal assets while accommodating rapid renewable growth. It would also offer a template for coal-dependent economies seeking to integrate variable renewables without compromising reliability.

Afghan Deputy PM Baradar inaugurates professional extraction at Balkhab mine

Afghan officials recently launched professional coal extraction operations at the Balkhab coal mine in Sar-e-Pul province, marking a significant step in the country's efforts to harness its natural resources for economic development.

The project was inaugurated by Deputy Prime Minister for Economic Affairs, Mullah Abdul Ghani Baradar, during an official visit to the northern province. The initiative includes both the professional extraction of coal and the construction of key roads linking several mining sites across Balkhab district.

Speaking at the inauguration ceremony, Baradar emphasized the importance of adding value to Afghanistan's natural resources through domestic processing and production rather than exporting raw materials.

According to Baradar, the Balkhab coal basin is one of Afghanistan's richest mineral zones. The extraction project is being led by the National Development Corporation (NDC), which has already constructed over 200 kilometers of standard gravel roads to connect various mining sites in the district.

Baradar also assured local residents that coal needed for personal and household use will be made available at affordable prices. He added that the government plans to expand social services in Balkhab, including the construction of roads, hospitals, and other vital infrastructure.

Around 100 mining shafts have been drilled to date, employing over 2,000 workers directly. The mine is expected to produce approximately 500,000 metric tons of coal annually.

Authorities say the project will contribute significantly to Afghanistan's energy production and industrial development. It is also expected to reduce reliance on imports, generate employment, and boost the national economy.

Meet the "Coal-igarch" Jim Grech, CEO of Peabody Energy

Jim Grech, president and chief executive officer of Peabody Energy Corp, speaks during the 2023 CERAWeek by S&P Global conference in Houston, Texas

On a Friday evening in May, officials at the Michigan-based utility Consumers Energy received an unusual order. Trump's Department of Energy, citing a "national energy emergency," ordered the J.H. Campbell coal plant on the shores of Lake Michigan, slated for June 1 closure, to remain open.

"What was surprising about this order is that nobody was asking for it," said Dan Scripps, chair of the Michigan Public Service Commission, in an interview with The New York Times. Neither the utility nor the state requested this, and Michigan energy officials estimate that the additional cost to consumers of keeping the 63-year-old plant open will be $279 million annually.

On August 21, the Trump administration extended the order for an additional 90 days, the statutory maximum for such an emergency. These actions are an extraordinary and unprecedented federal intervention in state-level utility regulation—and a Trump era payback to the fossil fuel oligarchs who helped get him elected.

How is it possible that zombie coal plants, costly and polluting dinosaurs of a bygone era, could be resurrected for a second life? Only with the interventions of "coal-igarchs" like Jim Grech, CEO of Peabody Energy, can these energy relics remain. Peabody, formerly Peabody Coal, is a mining conglomerate, founded in 1883. It is a leading coal producer, operating 17 surface and underground mines and with 5,000 employees across the United States and Australia.

Yes, that Peabody. Singer John Prine, in his famous song, "Paradise," recounts returning to western Kentucky to visit the mountain town where his father was raised, only to find a ghost town: "I'm sorry my son, but you're too late in asking. Mr. Peabody's coal train has hauled it away."

Coal burning in the US has been in steady decline for decades because of its rising cost and its status as the most polluting form of all fossil fuels, accounting for roughly 40% of the planet's carbon dioxide emissions, according to the Global Carbon Project. In 2000, half of US energy came from coal. By 2023, coal's share had shrunk to 16.2%, replaced by less expensive gas, solar, wind, and other renewables. Since 2000, 780 coal-generating units have been shuttered and half the remaining 400 facilities are scheduled for retirement, according to Global Energy Monitor.

In true oligarch fashion, Grech has used his position, power, and wealth to lead efforts to elect Trump, appoint fossil fuel-friendly administrators, and implement their long-sought program of dismantling climate protections while ginning up coal consumption for a few more years. The Climate Accountability Research Project listed Grech as a 2024 "Climate Criminal" for his role in "running out the clock" for timely climate action and as an "enemy of the earth." And that was before Grech's intervened in federal policy this year.

Grech is a happy warrior for coal, traveling by corporate jet from his home in Miromar Lakes, Florida to company headquarters in St. Louis and Brisbane, and to DC to counter the anti-coal "negative publicity campaign." In a late-June interview for energy investors, Grech effused, "It's safer to work in a US coal mine than to work in a shopping mall or supermarket" and that "the world is turning towards coal not away…. We are the solution to the energy needs of the world and we aren't the problem." Citing the increasing demand for AI data centers, Grech says coal is superior to "weather dependent energy."

As a leader of Americas Power, a pro-coal lobbying group, Grech advanced the idea that coal plants should be kept open because of a national energy emergency, even though coal remains the worst polluting and most expensive energy source. Just like manufacturing a crime wave to justify federal military intervention into US cities, Trump energy officials have hyped the risk of summer power outages in the Midwest to justify emergency pronouncements.

Grech has a "coal-centric" worldview and political agenda. In an interview on Veritan, Grech states repeatedly that, "putting aside the carbon issue," coal is the answer to the world's hunger for electricity. This is despite many US states and European nations' transitioning away from coal with cooperation from state regulators and consent decrees with organizations like the Sierra Club.

The US has tremendous coal reserves, Grech opines, with Peabody's North Antelope Rochelle Mine in Wyoming, which mined 60 million tons of coal in 2024 and holds 1.3 billion tons of "proven and probable reserves." But domestic markets are limited by strong anti-coal environmental legislation and utilities shifting to renewables. And export to Asian markets, including India and China, is thwarted by the absence of West Coast ports. If the coal oligarchs get their way, watch for federal action to override the opposition from California, Oregon, and Washington to coal-export terminals.

Grech and fossil fuel industry players raised millions for Trump's reelection campaign. At an April 2024 meeting on energy policy at Mar-a-Lago, Trump raised millions from fossil fuel industry players through a boldly transactional request for up $1 billion for his campaign. He pledged to scrap Biden-era regulations and said, according to attendees, that giving $1 billion would be a "deal" in terms of the taxes and regulations they would avoid thanks to him. Grech and Peabody's PACs gave over $100,000 to Trump and a handful of coal-friendly congressional Republicans.

On January 20, Inauguration Day, Trump signed an executive order "Declaring a National Energy Emergency," directing federal agencies to speed up energy projects such coal mining and drilling for oil and gas. Trump immediately nominated a cadre of fossil fuel industry boosters in key positions, including oil services company executive Chris Wright as secretary of energy, who appointed Alex Fitzsimmons to the Office of Cybersecurity, Energy Security, and Emergency Response. Fitzsimmons, a Grech ally who had worked for several Peabody-funded organizations, worked on advocacy efforts to roll back the Clean Power Act.

Grech was present at the White House on April 8 when Trump signed an executive order, "Reinvigorating America's Beautiful Clean Coal Industry," that prevented closure of coal plants under the Federal Power Act and lifted a moratorium on drilling and mining on federal lands. Six days later, Peabody announced the signing of seven-year contract with Associated Electric Cooperative to provide 7 to 8 million tons of coal per year to Midwestern coal-generating stations. The value and terms of the contract are not public, but its estimated value is, at minimum, over $5 billion, not including the cost of transporting the coal from Wyoming to Midwest utilities.

The DOE's Fitzsimmons issued the May 23 order to keep the J.H. Campbell power plant open, citing "national security considerations." A leaked DOE memo revealed that Fitzsimmons fully understood the practical and financial challenges of closing the plant but pressed ahead.

The J.H. Campbell coal plant scrambled to comply with the Trump administration's order. After allowing the plant's coal reserves to dwindle, in anticipation of the June 1 closure, Consumers Energy worked to keep retiring staff on board and locate the 15,000 tons of coal per day the plant needs to operate. A spokesperson from Consumer Energy told me they are sourcing it from Wyoming's Powder River Basin on an ongoing basis to comply with the order, but declined to disclose which with company. Peabody Energy remains one of the largest mining operators in the PRB.

In Michigan, protesters took to the streets to protest keeping the Campbell plant open. At an August 15 demonstration at the office of US Representative Bill Huizenga, environmental activist Indigo Umlor told the Michigan Advance that Huizenga "has chosen to align with MAGA politicians and align with keeping this plant open for longer. This plant is costing about $1 million a day to stay open, and in the last five weeks has cost taxpayers about $30 million."

Grech and his pals love Trump's executive orders and deregulation moves, but must, in Grech's words, "make it stick through legislation."

In addition to politicians like Huizenga, we need to know the names the oligarchs, like Jim Grech, who are often the invisible powers behind the coal-gilded throne.

Australian lobby group calls for investigation into alleged foreign investment in climate activism

An Australian coal industry lobby group has called national intelligence agencies to investigate alleged foreign involvement in unnamed "activist groups" it claims are threatening the nation's prosperity.

Coal Australia also called on the government to expand restrictions on foreign donations to block money being funnelled to environmental groups, and to introduce powers allowing authorities to terminate grants or strip charity status from organisations that fail to disclose funding sources.

The demands were set out in one of nearly 150 submissions to a parliamentary inquiry into the spread of climate change-related misinformation and disinformation.

It comes as thousands of climate activists prepare for November's annual People's Blockade of coal exports, which organisers from the grassroots group Rising Tide have described as the "biggest and boldest yet."

The lobby group, whose members include Whitehaven and Yancoal, argued Australia's prosperity was being "compromised" by activist groups with foreign backing.

It recommended that electoral and intelligence agencies deliver a joint annual report to parliament on threats to the country's energy security, citing "malicious" foreign interference and the dissemination of false information.

The submission did not name agencies, though the Australian Security Intelligence Organisation is responsible for monitoring foreign influence.

It also proposed that the first report include an audit of all funding to activist groups not covered by existing foreign donation rules.

"Such reporting would also ensure maximum community awareness and vigilance of manipulative and deceptive campaign tactics," Coal Australia chief executive Stuart Bocking wrote.

The group previously said that the "coal boom" had been undermined in Australia, claiming that in 2023, foreign organisations had brought in $129 million AUD (£63m) of offshore money to support activist groups.

Coal-fired power plants vital to avoiding an energy blackout

Our country cannot afford the luxury of shutting down coal-fired power plants overnight without replacing them with other energy production capacities, because that would mean a real risk of a blackout, with devastating effects on the economy and on the daily lives of citizens, said Bogdan Ivan, the Minister of Energy, during a press conference he held recently at the PSD headquarters. The official pointed out that, although the authorities in Bucharest have assumed the most aggressive decarbonization target in the European Union through the PNRR, the promises made to the Commission in Brussels cannot be implemented in the absence of solid alternatives.

"If we were to close the coal-fired units at the Oltenia Energy Complex, we would really be at risk of blackout," the minister said, emphasizing that the gas-fired power plant projects that were supposed to replace these capacities exist only on paper, while the pressure of the deadline at the end of 2025 is approaching at an alarming speed.

In order to avoid sanctions from the European Commission, Bogdan Ivan announced that he had already sent arguments and clarifications to officials in Brussels, trying to create the framework through which he could maintain at least three active coal-fired units and two reserve ones.

But the challenges do not stop at the coal issue. The energy price crisis and its impact on the population and the business environment will end up on the agenda of the Supreme Council for National Defense.

Bogdan Ivan stated: "I had a constructive discussion with the President of Romania on this subject and on the main themes, including the area of solutions. During this day, I submitted the draft memorandum proposal to the Government of Romania, because procedurally the Prime Minister proposes that this memorandum be integrated into the CSAT agenda".

The Minister of Energy mentioned that the document, which contains a "very clear" analysis of the energy situation, identifies major scenarios and risks in the event that major investment projects remain blocked due to bureaucracy.

According to the data presented by Mr. Ivan, our country is today in the top of European countries with the highest energy prices, a factor that puts pressure on the population's budget and reduces the competitiveness of companies. "Romania is going through a complicated period from an economic point of view, and a major contribution to this element is the high price of electricity," said the energy minister, pointing out that PSD - the political party to which he belongs - is coming up with a recovery plan focused on increasing domestic production and stimulating investments.

One of the key directions is to provide facilities for companies that use natural gas as a raw material in a proportion of over 30% of the final cost of products.

"Romania has already become the largest producer of natural gas in the European Union, and this means that we automatically have a very varied offer, which will bring additional stimulation for companies that invest in strategic industries," said Bogdan Ivan.

He showed that the huge trade deficit, of over 33 billion euros last year, is based on two-thirds of the energy-intensive and petrochemical industries. Through the fiscal incentives proposed by the Social Democrats, the deficit could be reduced annually by 500-700 million euros, money that would be transformed into taxes to the budget, jobs and economic diversification. "Our goal is to reduce the trade deficit and strengthen the national economy," said the energy minister, explaining that Romania needs a strategy that transforms natural resources into a competitive advantage.

Another major problem remains the dependence on energy imports. "Romania, in the last 10 years, has transformed itself from a net energy exporter into a net importer, in the context of removing approximately 7,000 MW of capacity from production and replacing only around 1,200 MW. At a time when we import approximately 22% of all Romanian consumption, we are dependent on the price on international exchanges," Bogdan Ivan specified.

The PSD's proposed solution is to create a fund for strategic investments in production capacities in the band, focused on nuclear projects - reactors 3 and 4 at Cernavoda and SMR technology - as well as new gas-fired plants. The plans aim to add, in the next seven years, 12,000 MW in production and 2,800 MW in storage, which would transform Romania from an importer to a net exporter of energy, which according to Mr. Ivan would ensure cheaper energy for the population and stability for the industry. Bogdan Ivan also showed that the financing solution is not based only on grants, but on modern financial mechanisms that multiply the resources attracted. "The Social Democratic Party comes with a package of financial instruments that combines non-reimbursable European resources, resources from the Modernisation Fund and financial instruments that can bring four or five times more capital in strategic investments," explained the Minister of Energy.

He pointed out that only through strategic investments, through flexibility in negotiations with the European Commission and through concrete measures to stimulate the industry, our country can avoid the energy collapse and can once again become a strong regional actor in the energy field. "The targets are very clear: facilities for companies, reducing the trade deficit and transforming Romania from a net energy importer into a net exporter.

Aceh to Get New Coal Port with $85m NCN Investment

A miniature model showcases PT Nagan Cipta Nusantara's planned Rp 1.4 trillion coal terminal and 10-kilometer hauling road project in Nagan Raya, Aceh. The port is expected to handle up to 12 million tons of coal annually. Undated photo.

Jakarta. Nagan Cipta Nusantara (NCN) has unveiled plans to develop a dedicated coal terminal port and a 10-kilometer hauling road in Nagan Raya, Aceh, with an investment of Rp 1.4 trillion ($8.4 million). The announcement was made at the Coaltrans Asia 2025, Asia's largest coal industry conference and exhibition, held on Sept. 21–23 at the InterContinental Bali Resort.

The project will be developed in stages, beginning with a coal terminal and the hauling road, before expanding to include a crude palm oil (CPO) port. The coal terminal is expected to begin operations in the second quarter of 2026.

Aceh is among Indonesia's largest coal-producing regions but has long faced bottlenecks due to limited port infrastructure. NCN's integrated mine-to-port model is aimed at lowering logistics costs and reducing reliance on distribution routes outside the province.

The Nagan Raya port will have a minimum handling capacity of 40,000 tons per day, with export potential reaching 1 million tons per month, or 12 million tons annually. India, located just northwest of Aceh, is expected to be a key market.

NCN estimates the port could generate $4 million (Rp 59 billion) per year in regional revenue -- more than half of Nagan Raya's 2024 local revenue of Rp 99.76 billion. In addition, the project is projected to contribute $18 million (Rp 295 billion) annually in non-tax state revenue and around $360 million (Rp 5.9 trillion) in foreign exchange earnings.

"The Nagan Raya terminal project is not just about infrastructure, but also about positioning Aceh as a significant player in coal and other commodities, including CPO, at both the national and global level," NCN founder Rangga Cipta said in a statement on Monday.

NCN said the development will also bring local, regional, and national benefits. As part of its sustainability commitments, the company pledged to build the port and hauling road in compliance with environmental and safety standards, including measures to mitigate impacts on marine and terrestrial ecosystems, waste management, and pollution control. The project will align with both central and provincial government policies to support a greener and more responsible economic growth path.

Ventilation in underground mines

Ventilation systems are indispensable to the safe and efficient operation of underground mines. The accumulation of hazardous substances such as methane, carbon monoxide, coal dust, and the depletion of oxygen can result in catastrophic events including fires and explosions. To mitigate these risks and ensure that mining activities are conducted under secure conditions, the implementation of robust and effective ventilation systems is imperative. This paper examines the foundational principles of underground mine ventilation, the technologies employed, the challenges encountered, and contemporary solutions supported by scholarly research.

Historical Development of Underground Mine Ventilation
The issue of ventilation in subterranean mining environments has a long and complex history. In antiquity, miners contended with adverse atmospheric conditions using rudimentary methods such as manually excavated tunnels and reliance on natural airflow. Civilizations such as the Egyptians and Romans utilised small shafts and openings to facilitate air circulation.

During the 16th and 17th centuries in Europe, the increasing depth of mines exacerbated ventilation challenges. By the 18th century, particularly in coal mines, the frequent accumulation of methane gas led to a surge in explosion incidents, thereby necessitating the development of more effective ventilation mechanisms. Mechanical fans were first introduced in England during this period, and engineers such as George Stephenson pioneered the use of engines to regulate airflow. These innovations marked a significant advancement in controlling subterranean air quality.

By the late 19th century, further refinements were made, including the development of ignition-resistant fans designed to prevent methane-induced explosions. From the mid-20th century onward, scientific inquiry and technological progress have continued to enhance the efficacy of ventilation systems. In recent years, the advent of automated and computerized systems has significantly improved safety standards in underground mining operations.

PRIMARY OBJECTIVES OF UNDERGROUND MINE VENTILATION

The principal aim of ventilation in underground mines is to provide workers with a continuous supply of fresh air while eliminating harmful gases, dust, and other airborne contaminants. The key objectives include:

- **Elimination of Gases and Dust:** Preventing the admixture of methane and dust generated during extraction and blasting activities with ambient air,and ensuring their effective removal.

- **Climatic Regulation:** Maintaining optimal temperature and humidity levels to safeguard worker health.

- **Extraction of Hazardous Gases:** Operating ventilation systems to prevent the ignition of methane and to efficiently extract gases such as methane and carbon monoxide.

- **Mitigation of Fire and Explosion Risks:** Reducing the concentration of flammable gases to minimize the likelihood of explosions.

GLOBAL PRACTICES IN UNDERGROUND MINE VENTILATION

Ventilation systems vary internationally, reflecting the specific geological and operational conditions of each region. In the United States, the "split ventilation" method is widely adopted to manage methane concentrations effectively. Australian mines employ dynamic ventilation systems that periodically alter airflow direction, thereby enhancing the detection and control of methane levels and reducing explosion risks.

DESIGN AND TECHNICAL SPECIFICATIONS OF VENTILATION PLANS

A ventilation plan must be meticulously tailored to the environmental and operational characteristics of the mine. Essential components include:

- **Air Volume and Flow Rate Calculations:** Airflow must be allocated per worker, with increased rates in mines exhibiting elevated methane levels.

Methane Concentration	Airflow Rate (m^3/min)
Low	1-2
Moderate	3-6
High	20-25

- **Safety and Redundancy Measures:** Ventilation systems must remain operational during power outages or equipment failures. Accordingly, backup generators and integrated monitoring and alert systems are required.
- **Intake and Exhaust Mechanisms:** Mechanical ventilation systems must utilise fans certified as explosion-proof ("Ex-proof") to prevent ignition, particularly in methane-rich environments.

TECHNOLOGICAL ADVANCEMENTS AND SCIENTIFIC RESEARCH

Modern ventilation systems increasingly rely on advanced technologies. Computer-based simulation tools enable real-time monitoring of airflow and gas concentrations, thereby enhancing system responsiveness and safety. For instance, McPherson *et al*. (2015) introduced simulation methodologies that model airflow and methane distribution, contributing significantly to the development of more effective safety protocols.

PRACTICAL APPLICATIONS AND INTERNATIONAL CASE STUDIES

Numerous countries are actively pursuing innovations to improve ventilation efficiency. In Russia, a "multi-fan" configuration is employed to achieve uniform airflow distribution. In China's Gongchangling mine, automated systems continuously monitor air volume and flow rate via sensors, adjusting fresh air supply in real time to maintain optimal conditions.

CONCLUSION

Ventilation is a critical component of underground mining operations, essential for protecting worker health and maintaining a safe working environment. Effective systems not only prevent the buildup of hazardous gases but also reduce the risk of fires and explosions. The integration of modern technologies and simulation tools has further refined ventilation practices, enabling tailored solutions for diverse mining conditions. As the industry continues to evolve, the advancement of ventilation systems remains central to ensuring operational safety and sustainability.

Accelerating just transitions for the coal sector

NET ZERO REQUIRES A RAPID TRANSITION AWAY FROM UNABATED COAL-FIRED POWER

Achieving the goal adopted at COP28 of net zero emissions of greenhouse gases from the energy sector by 2050 hinges critically on the rapid transition away from the unabated use of coal for generating electricity. The scale of the task cannot be overstated: coal accounts for over one-third of global power supply, in many cases from recently built plants. As the most carbon-intensive fuel, coal's role in emissions is even bigger: globally, coal is responsible for over 40% of all energy sector CO2 emissions. If existing coal power plants and industries were to continue to operate as they do today, they would "lock in" emissions pushing the world well beyond the 1.5 °C limit.

Global coal demand grew in 2023, despite rapid growth in renewables-based power generation. The largest uptick was observed in the People's Republic of China (hereafter, "China"), followed by India and other emerging and developing economies. Growing use of coal, mainly for power, has accounted for nearly all the increase in global CO2 emissions since 2019. According to the latest IEA estimates, clean energy deployment since 2019 has helped to avoid coal demand of around 580 million tonnes of coal equivalent per year on average – equivalent to the coal demand for power generation of Indonesia and India combined.

A growing number of countries have adopted net zero emissions pledges, which is tantamount to phasing out completely the unabated use of coal and other fossil fuels. At the end of 2023, those pledges covered more than 85% of global energy sector emissions. More and more countries have also made specific commitments to phase down or out the use of unabated coal in power, covering 30% of current coal-fired generation – up from less than 20% in 2022.

COAL TRANSITIONS HINGE UPON A FAST SCALE-UP OF LOW-EMISSIONS POWER SOURCES

Reducing reliance on unabated coal-fired power generation is possible only if alternative sources of power are developed quickly enough to meet rising electricity demand. In the Announced Pledges Scenario (APS), where all climate commitments made by governments worldwide are met in full and on time, nearly 75% of the drop in global coal-fired generation over 2022-2050 is compensated for by solar PV and wind power, followed by hydropower and other renewables and nuclear. At COP28, governments committed to tripling renewable capacity by 2030 in line with the IEA's Net Zero Emissions by 2050 Scenario, which if achieved, would be a crucial accelerant in the transition away from coal powered generation. The latest assessment of the announced pipeline of renewable power projects indicates that if these come to fruition, the world would already be nearly three-quarters of the way to the tripling target. However, critical investment gaps persist in many emerging market and developing economies.

Shifting coal plants from baseload generation to more flexible operation will reduce coal use while supporting the integration of alternative sources of electricity generation. This would lower emissions while preserving electricity security and can reduce the near-term impacts on jobs and the local economy. In the APS, the capacity factor of coal plants in emerging market and developing economies falls from around 55% in 2022 to around 45% in 2030, and around 40% in 2040. Alongside repurposing these plants towards providing grid support, countries should align their grid operation protocols and compensation schemes to encourage coal plants to operate more flexibly, which can also help offset the revenue losses associated with lower capacity factors. Some plants are also retired before their technical lifetimes, while others are retrofitted with carbon capture, utilisation and storage (CCUS) technology or co-fired with low-emissions fuels such as ammonia or biomass. The potential for adopting these approaches varies by country, and could consider a blend of direct regulation, financial incentives and market-based measures.

NEW APPROACHES ARE NEEDED TO SPEED UP THE FINANCING OF COAL TRANSITIONS

Favourable economics for renewables will not, on their own, be sufficient to achieve the rapid transition away from coal power. In many regions, new renewables offer lower levelised costs of energy than the cost of operating existing coal plants. However, this is not the case everywhere, and in some regions coal plants have contract or dispatch agreements which shield them from market competition. Addressing these barriers and incentivising investment in low-emissions power is imperative to unlock the transition away from unabated coal power and the full potential of renewables. Over 2023-2030 in the APS, USD 890 billion needs to be invested annually in low-emissions power capacity and support, such as grids and battery storage, with around a third of new low-emissions power capacity additions dedicated to replacing coal generation, instead of meeting incremental demand. Mobilising this investment depends critically on bringing in more private sector investment, and finding the right financing mechanisms that address the problems posed by today's high interest rate environment, particularly in emerging and developing economies.

Policies to facilitate the financing of clean energy must go hand-in-hand with measures to end financing for new coal power and to finance the early retirement of some coal assets. Over 2023-2030, around 20 gigawatts of coal power plants operating today are retired before they reach 30 years in the APS. For many of these plants, especially in the emerging market and developing economies, large amounts of capital invested in them have yet to be recovered. There is no single blueprint for phasing out coal-fired generation. A variety of innovative financing mechanisms are under development to help shorten payback periods, refinance and restructure debt, and adjust contract terms in ways that avoid undermining investor confidence. In many regions, such policies must take account of the role currently played by coal in ensuring security of supply.

COAL TRANSITIONS CAN BE ACHIEVED AFFORDABLY

Maintaining affordable electricity prices throughout the transition is paramount. In the APS, power sector investments climb steeply to 2030, but the costs of replacing coal generation and the system services it provides with low-emissions sources are more than offset by the fuel cost savings from reduced fossil fuel demand in the longer term. Appropriate policy frameworks can help ensure that the costs of these investments are recovered over a longer period, helping reduce the impact on the average cost per unit. In the APS, average electricity prices worldwide decline by over one-fifth between 2022 and 2050, though savings vary by region according to initial levels, carbon pricing and growth in electricity demand.

POLICIES TO TRANSITION AWAY FROM COAL POWER MUST BE PEOPLE-CENTRED AND JUST

Accelerating coal transitions will impact workers and communities that depend on coal. For that reason, comprehensive stakeholder engagement and a set of policies to manage negative impacts, including on energy affordability, energy access and socioeconomic development, are essential. These need to cover the creation of decent work opportunities, support for workers affected by energy transitions and respect for fundamental labour principles and rights. Several countries, including Canada, the Czech Republic, Germany, Spain and South Africa, have convened national task forces or commissions to evaluate the socio-economic effects of coal transitions. The IEA has established its Global Commission on People-Centred Clean Energy Transitions to codify best practices.

National pledges to cut emissions and decarbonise power generation, if fully implemented, would inevitably lead to job losses in the coal sector, especially in mining. In the APS, total coal employment declines from 7.8 million people worldwide today to 5.6 million in 2030. Just over half of those job losses result from a fall in coal production, with the remainder attributable to mechanisation, automation and other improvements in labour productivity. Declines in coal employment have been navigated in the past in parts of Europe and North America, and more recently in China. Managing the economic and social consequences of coal transitions is vital to enduring progress on reducing energy sector emissions. New policy approaches are proving effective, including short-term income support, education and training, and new career opportunities for coal workers who are made redundant. At the end of 2023, just 14% of coal workers in coal-dependent countries were covered by such just transition policies, though this represents an improvement of 10 percentage points over 2022.

The social and economic impacts of transitioning away from the use of coal for power generation vary widely across and within countries, according to resource endowments, the structure of the economy, level of economic development, and the importance of the coal industry to local labour markets. National exposure to coal, as measured by our Coal Transition Exposure Index (CTEI), is highest in Indonesia, followed by Mongolia, China, Viet Nam, India and South Africa. Many coal regions in those and other emerging economies are characterised by low levels of economic diversification, limiting opportunities for alternative activities and jobs. Coal transition policies must seek to cushion the impact of job losses while supporting economic development through measures such as industrialisation or environmental rehabilitation initiatives.

CO-ORDINATED EFFORTS ARE NEEDED TO ACCELERATE COAL TRANSITIONS AROUND THE WORLD

Commitments to transition away from unabated coal use for power set a direction; concrete policies are needed to meet them. Reaching long-term net zero goals requires unambiguous policy settings and near-term targets, which should be reflected in upcoming NDCs. While each country's circumstances vary, the global pledge to triple renewables and double efficiency by 2030 implies a coal transition, but this itself does not guarantee the reductions in coal emissions needed to be aligned with meeting national climate ambitions nor our collective target of limiting warming to 1.5o C, underscoring the enduring importance of a dedicated focus on facilitating the global transition away from coal.

NEWS, PLANT AND EQUIPMENT

US offering leasing deals on federal lands for new mines

Federal land reserves of coal are being leased for mining in Alabama, Montana, Utah, Wyoming and North Dakota in new deals accelerating under Trump administration domestic energy directives.

A succession of coal lease deals for mines has taken place in the months following the US Department of Interior ending a past moratorium on federal coal leasing in lands under the oversight of the Bureau of Land Management.

US Interior Department Secretary Doug Burgum announced a commitment April 8 to fulfil directives by President Donald Trump's April 6 executive order to reinvigorate America's coal industry.

"The Golden Age is here, and we are starting to 'Mine, Baby, Mine' for clean American coal," Burgum declared. "Interior is unlocking America's full potential in energy dominance and economic development to make life more affordable for every American family while showing the world the power of America's natural resources and innovation."

Part of Trump's order directed the Interior Department to assess US coal resources and accessibility on federal lands.

The BLM administers federal land leases for new coal mines. The agency is in charge of 700 million acres of subsurface minerals.

Since April, the BLM has been actively offering coal leases for new mines and selecting winning bids.

"Coal has long been the backbone of America's energy and industrial strength," Burgum noted in a Sept. 2 announcement about three competitive coal leases in Alabama, Montana and Utah. "By moving forward with these lease sales, we are creating good-paying jobs, supporting local communities, and securing the resources that keep America strong. President Trump's leadership is putting American workers first and ensuring our nation's energy future is built on reliable, homegrown resources."

New Wyoming Coal Lease Offer Outside Gillette

The newest BLM lease for offer is 3,508 acres in Campbell and Converse counties, 15 miles south of Wright, about 40 miles south of Gillette. The deadline to submit sealed bids in the competitive lease process is Oct. 8.

"The tract is located adjacent to the Antelope Mine's current operation and contains approximately 445 million tons of coal of which approximately 365 million tons are considered to be mineable," described a Federal Register notice issued Sept. 25. "A lease issued as a result of this offering will require payment of an annual rental of $3 per acre, or fraction thereof, and a royalty payable to the United States."

The winning be will be the highest cash amount offered by a qualified bidder if that bid meets/exceeds the BLM's estimated fair market value for the tracts.

Kris Kirby, acting state director of the BLM Wyoming, issued a Sept. 24 announcement about the coal lease offer on federal land. "This lease sale exemplifies BLM's vital role in strengthening America's energy independence and positioning Wyoming for long-term economic opportunities," Kirby said. "The BLM is committed to the responsible management of public lands, bolstering domestic energy production while benefiting local communities."

120 Acres of Federal Land Offered for Utah Coal Lease

The BLM issued a public notice issued Sept. 10 about its intent to lease 120 acres of federal land thought to hold 858 thousand tons of recoverable coal in the Little Eccles Federal Coal Lease Tract. The Utah parcel is near Skyline Mine in east-central Emery County, about a three-hour drive south of Provo. Sealed bids are due Oct. 1.

"This project strengthens national energy security and will provide a boost to the local economy," Christina Price, BLM Utah's deputy state director for lands and minerals, stated in the announcement. "We are proud to be a part of the effort to provide Americans with an affordable, supply of domestic energy."

Two Alabama Coal Leases Offered On 4,050 Acres Under Private Lands

The BLM will be selecting winning bids on Sept. 30 for leases on two tracts under private lands in Tuscaloosa County, Ala. The tracts in the north-central area of the state (about an hour away from Birmingham) are estimated to have 53 million tons of recoverable metallurgical coal. This substance is designated critical material under the Energy Act of 2020 and is used in steel production.

Montana Federal Coal Lease for Estimated 167.5 Million Tons of Recoverable Coal

The BLM has set an Oct. 6 deadline for bids to lease a 1,262 acre tract in Big Horn County, Mont. The area is thought to have 167.5 million tons of recoverable coal. "The lease sale responds to an application by Navajo Transitional Energy Co. LLC, operator of the Spring Creek Mine. If issued, the lease could extend the mine's life through 2051, supporting high-paying jobs and contributing to US energy security," a BLM notice stated Sept. 2.

BLM Awards Coal Leases in North Dakota

This year, the BLM has selected winning bids in North Dakota:

- $79,996 from Falkirk Mining Co. of Underwood, N.D., to mine 11.3 million tons of available coal across about 800 acres at the Falkirk Mine in McLean County.

- $106,292 from Coteau Properties Co. of Beulah, N.D. to mine 8.3 million tons of available federal coal across 1,070 acres at Freedom Mine in Mercer County.

The BLM stated that both N.D. coal leases also will bring in $3 per acre in yearly rental fees plus a 7% royalty payment on coal produced. Paid royalties will be split 50/50 between the state and the US Treasury.

More Coal Mines on Federal Lands Likely

The federal government is moving forward with its first coal exploration project since 2019, the BLM announced in July.

Utah is the site for a proposed drilling by Canyon Fuel Co. LLC. The Salt Lake company wants to drill 10 exploratory holes on 9,276 acres of public land in rural Sanpete County, located about 50 miles north of Richfield.

"The project would use low-impact drilling methods to assess potential coal resources," according to the BLM Utah. Public input on the project was being sought by the BLM.

Conveyor safety and the return on prevention

Protecting workers should be the top priority for any employer, especially those on the front line of materials processing. Beyond the substantial financial consequences of a workplace injury or fatality, the impacts are felt profoundly by an employee's family, their coworkers, and the wider community.

Thus, investing in safe, well-engineered equipment and prevention-focused training that helps protect workers from injury or illness is essentially investing in people, company culture, and the community. And Martin's technicians are increasingly applying their expertise to help operators control maintenance risks by sharing their knowledge and installing equipment that improves safety. [**Figure 1**]

Although return on investment (ROI) is a common calculation when installing new conveyor accessories, some safety experts emphasize the return on prevention (ROP). This long-term strategy prioritizes equipment with safety engineered into the design, allowing for more ergonomic servicing, faster and easier access, and other improvements that make maintenance less dangerous and more desirable to do. Although safer equipment is typically a larger initial capital investment, the whole life return is in faster maintenance with less downtime, longer equipment life, and, importantly, a considerably lower chance of an incident, reducing the overall cost of operation.

THE REAL COSTS OF ROI

Calculating return on investment (ROI) on conveyor safety is specific to each operation, but in general, they can be

Figure 1: Guarding restricts access and may require a specific procedure to unlock.

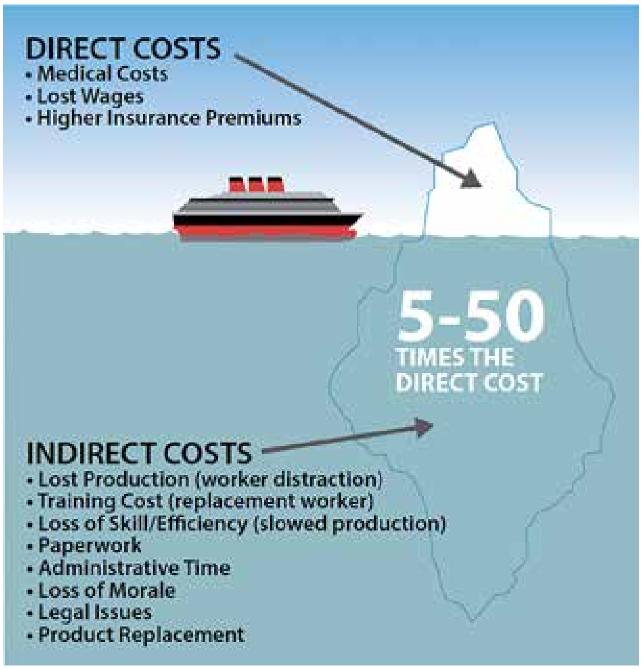


Figure 2: Direct and indirect costs of worker injuries and fatalities

broken down into "direct costs" and "indirect costs":

- *Direct costs* are explicitly associated with an accident or illness. In general, these include fines, medical bills, insurance premiums, indemnity payments and temporary disability payments.

- *Indirect costs* include a variety of other expenses resulting from the incident. They include: [**Figure 2**]

    - o Cleanup time and product loss
    - o Equipment repair / replacement
    - o Purchase / installation of safety components
    - o Overtime to fill in for the missing worker
    - o Cost of hiring, training and equipping new employees
    - o Legal fees and litigation costs
    - o Increased insurance premiums
    - o Production delays and missed shipment targets
    - o Reduced employee morale, greater absenteeism
    - o Negative publicity
    - o Increased scrutiny by regulators

THE PRICE OF RECOVERING FROM AN ACCIDENT

To demonstrate the benefits of safety to a company's bottom line, OSHA (the Occupational Safety and Health Administration in the USA) created the online tool, '$afety Pays', which uses company-specific economic information to assess the potential economic impact of occupational injuries on that firm's profitability. The program estimates direct costs (claim cost estimates provided by the National Council on Compensation Insurance) and indirect costs (provided by the Stanford University Department of Civil Engineering) and weighs them against financial details supplied by the company. [**Figure 3**]

RETURN ON PREVENTION (ROP)

The commonly used ROI model calculates the time frame in which the capital expenditure on new equipment is recaptured through the improvements. If a proposed project

Figure 3: OSHA $afety Pays Tool Example

Figure 4: Equipment like the Martin® track-mounted belt cleaners are

meets budget expectations and has a payback period of less than one year, plant management usually approves it.

Working with abstract numbers implicitly creates pushback, making it more difficult for safety-conscious managers to obtain approval for their proposals. However, the hard costs of worker injuries and fatalities are very real. The ROP model illustrates the direction and strength of occupational safety and health programs in helping to achieve company goals. [**Figure 4**]

designed to pull away from the system for safe ergonomic servicing.

CONCLUSION

The death or serious injury of a worker is always tragic and can have long-term impacts for all those involved. Investigations usually reveal that incidents could have been prevented with the right knowledge and behaviours, combined with practical and cost-effective safety improvements. The ROP on durable, well-designed conveyor accessories and professional training makes good financial sense and can lead to a safety culture that ripples throughout the company's balance sheet.

AUTHOR

Jerad Heitzler
Training Manager, Martin Engineering

New approach for monitoring the underground coal mines atmosphere using IoT Technology

The atmosphere in underground mines is considered one of the most dangerous places, where there is always a possibility of a fatal accident. In general, the atmosphere in underground mines consists of oxygen, nitrogen, carbon dioxide, carbon monoxide, methane, sodium hydroxide, hydrogen, and sulphur dioxide. These gasses can be classified as toxic and poisonous gasses[1]. The methane (CH_4) is one of the harmful gases, emanating from the strata and entrapped in the coal seam[2]. The methane is also known as fire damp that causes explosion and fire, when it reaches 5.4 to 14.8% in mixture of oxygen of 12.5 to 21%[3]. Further, the gasses like carbon monoxide (CO) and carbon dioxide (CO_2) are treated as the key toxic gasses. Whenever the percentage of CO and CO_2 increases, in mines environment, the percentage of O_2 reduces. This reduction of oxygen causes improper respiration to the miners and creates an uncomfortable situation to work[4]. Moreover, the degree of contamination of the mine air mainly depends on the various factors such as the length of working, mined rocks or minerals those content gas, the tendency of mineral or rocks to absorb oxygen and the method of working in the coal seam.

Thus, the mine air can be regarded as the constitute of three parts namely, atmospheric air, active gasses and dead air. The active gasses are toxic or explosive gasses that are formed or released in underground mines and mix with atmospheric air. The dead air is a mixture of carbon dioxide and nitrogen contained in the mine air in a quantity exceeding their contained in atmospheric air. The main objective of this paper is to facilitate the use of IoT technology in an underground environmental monitoring system. For this purpose, an IoT-based automatic gas and humidity monitoring system is developed, which is able to provide a warning signal in case of emergency (when the measured gasses and humidity exceed the allowable limit). In addition, the developed system is tested in the laboratory to measure methane, carbon monoxide, carbon dioxide and humidity. Then, the readings are compared with digital multi gas detectors and hygrometers to verify the accuracy of the developed gas monitoring system. The monitoring system is characterised by its uniqueness: It is real-time, wireless, and low-cost. This system would provide sufficient data storage to help predict the mine environment and allow mine officials to take the necessary preventive measures when it comes down to it.

Any change in the permissible limits for mine gasses can be harmful to miners working in this atmosphere. The constant operation of heavy machinery and the absorption of oxygen in the coal seam cause oxygen levels to drop, resulting in unpleasant conditions for miners underground. This uncomfortable condition reduces the miners' performance and affects the overall production rate. Therefore, fresh air must be supplied to the atmosphere underground to bring the oxygen content up to the required level. At all points in the mine where people must work or pass, the air must not contain less than 19% oxygen or more than 0.5% carbon dioxide or other harmful gasses in quantities that could affect miners' health. To calculate the amount of air drawn in (which is directly dependent on the capacity of the fan), it is necessary to know the percentage of underground mine gasses (such as CH4, CO and CO2) so that effective ventilation can take place[6]. Therefore, before installing a ventilation fan, it is very important to know the percentage of harmful and toxic gasses present in the atmosphere of underground mines. There are various techniques and instruments to determine the presence of the above gasses. These instruments are portable devices carried by miners to detect mine gasses. However, the major disadvantage of these gas detection devices is that the person has to enter the hazardous underground mine environment to detect the percentage of gasses, which is called discontinuous gas monitoring system[7]. The discontinuous gas monitoring system does not provide the actual information about the atmospheric gasses in the underground mines at any time of mining. Another disadvantage of these measurements is that the data recorded by the instrument cannot be stored in the detector device[8]. Thus, these measurement techniques do not provide real-time monitoring data on the gasses in the underground mines. Subsequently, it is necessary to use a continuous gas monitoring system for underground mining to improve miners' safety. The continuous gas monitoring system uses technology that provides real-time gas monitoring data at any point during the work. Continuous gas monitoring systems can be divided into mechanical and electronic gas monitoring systems. In the mechanical gas monitoring system, there is no way to report a hazard to no countermeasures, and mine safety measures are taken when the gas exceeds the allowable limits[9]. In addition, there is no suitable way to store the data of the measured gasses to predict future hazards. Thus, mechanical technology also does not seem to be an alternative solution that can take predictive safety measures for underground work, as it is limited and does not meet the legal requirements. In addition, humidity and air temperature in underground mines play a very important role in optimizing the performance of man, machine and material[10]. In previous literature, it has been found that humidity has a greater effect than air temperature in underground work. If a miner is exposed to excessive humidity for a prolonged period of time, it can lead to heat stroke and dehydration. This affects the overall work in underground mines[11]. Therefore, it is necessary to control the humidity in underground mines by using appropriate humidity measurement methods at regular intervals.

The safety of underground structures can be improved by shifting safety features from preventive to predictive measures by using appropriate measurement techniques. The preventive measurements help in predicting future accidents and thus contribute to improving the safety of miners in hazardous conditions. Therefore, there is a need for a suitable technology that can perform continuous monitoring of gasses and is also capable of storing the measurement data to assess the future risk of actions. The introduction of the Internet of Technology (IoT) into the underground gas monitoring system provides an opportunity to shift safety functions from preventive to predictive measures. The use of IoT technology in the gas monitoring system for coal mines helps to inform the safety personnel about the danger and is also able to take countermeasures against the gasses when they exceed the permissible limit. IoT technology is an emerging concept that has sufficient potential to run everything in a virtual environment[12,13]. It offers the flexibility to enable an automatic alarm signal both underground and at the surface of a mine. The application of IoT technology facilitates the work and improves the quality of the work[14-17]. IoT technology is nothing, but web connectivity of physical devices used in daily life. It basically consists of electronic devices, Internet connectivity, and other forms of hardware such as sensors. These devices and sensors can communicate with the cloud through certain connectivity features[18]. Once the data is transferred to the cloud, the software processes the data and triggers an action, such as sending an alert or automatically controlling the devices or sensors, without the need for a third party or user. The IoT can be used in the mining industry (due to its wide range of applications) in a number of ways, such as optimizing costs, improving productivity, ensuring the safety of people and equipment, switching from preventive to predictive maintenance, improving rapid decision-making, etc. The biggest advantage of IoT in mining is that it facilitates the use of artificial intelligence (AI), which transforms mining operations from human-centric to process-centric[19-21].

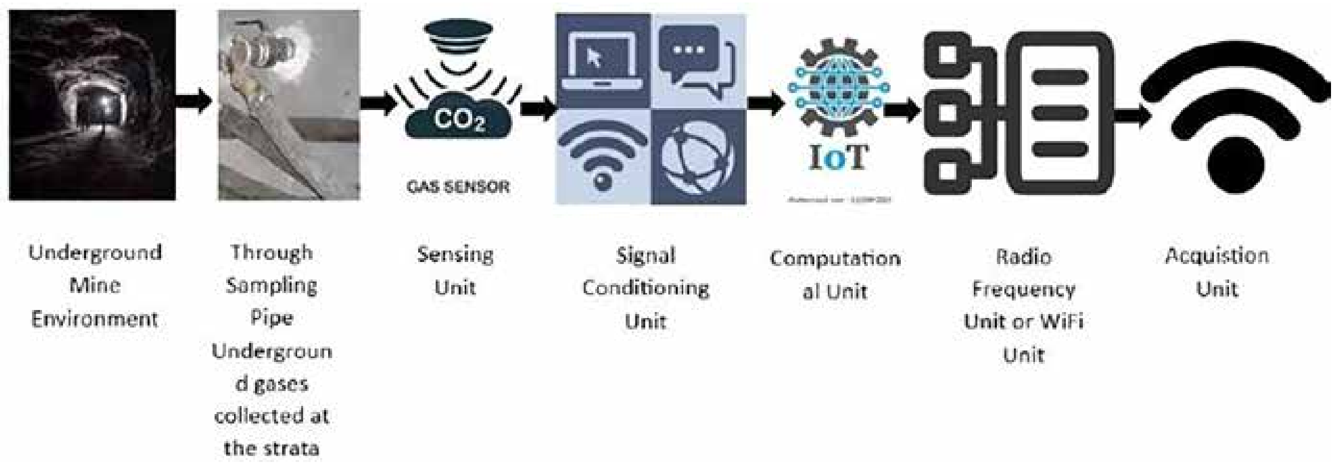


Figure 1: Block diagram of proposed monitoring system.

SYSTEM ARCHITECTURE AND DEVELOPMENT OF MONITORING SYSTEM

Typically, the IoT monitoring system consists of two main sections, the transmitter section and the receiver section. Both sections are powered by a battery, and the receiver is connected to PC or a cloud server (as shown in **Figure 1**). Normally, various functions are performed in the transmitter section, such as sensing, signal processing, computational core, and radio receiver. The required information is acquired by the transmitter unit and transmitted to the receiver area, where decoding of the acquired information is performed. Basically, the function of the receiver section is almost identical to that of the transmitter section[22-24]. An automatic IoT-based gas monitoring system was designed and developed to monitor the atmosphere in underground mines, and the experiment was conducted to verify its efficiency. The proposed system was specifically designed to collect information about atmospheric parameters in underground mines. The block diagram and system architecture of the proposed monitoring system are shown in **Figure 1** and **Figure 2**. The developed monitoring system consists of four units, namely, an extraction unit, an analysis unit, a transmission unit, and an automatic control unit. The suction unit collects the gas samples through the sampling tube and transfers them to the analysis unit, where the required sensor node detects the respective gasses. The extraction unit draws in the sample air using a vacuum pump so that the sample air can be passed to the analysis unit to measure the percentage of gasses in the sample air. The analysis unit is positioned at the surface where it has access to sufficient internet to do its job. After the analysis unit, the information about the measured gasses is forwarded to the transceiver unit, which is called the transmitter unit and consists of a Wi-Fi and a GSM module.

The sensing node is one that consists of all sensors for measuring the atmosphere of the mine environment. Its basic function is to sense and measure the atmospheric information such as gasses, air temperature and humidity the mine environment. Usually, sensing node are comprised of sensor modules, a microcontroller, and wireless transmitters. In this study, sensing node Arduino UNO was used as microcontroller that facilities the intermediate service between sensors and transmitters. Selection of appropriate sensors for monitoring a mine environment is a relatively complicated task. It demands consideration of several factors, such as measurement range, accuracy, and sensitivity. The technical specification of the sensors usage for the current study is presented **Table 1**.

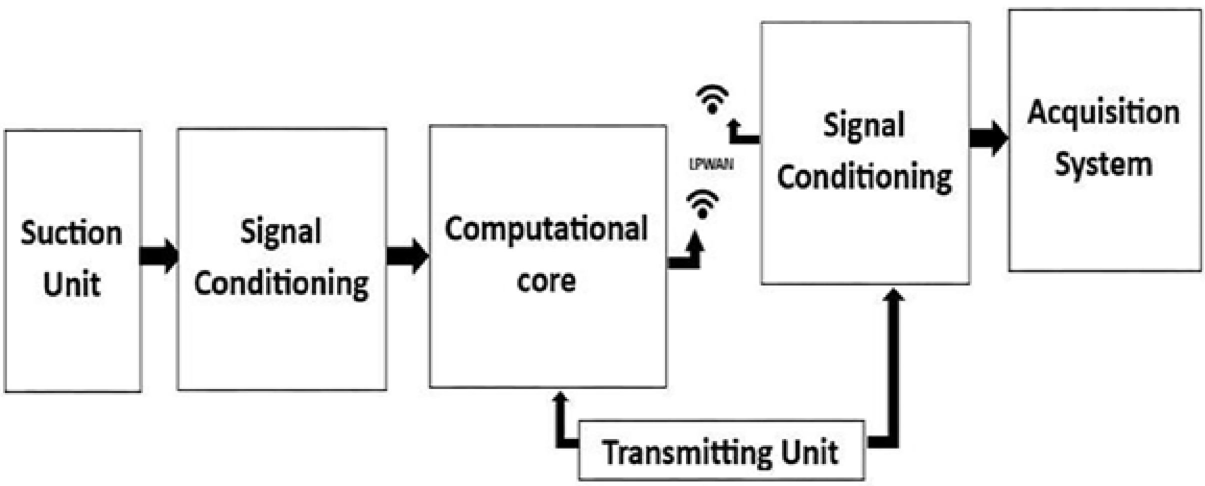


Figure 2: System architecture of proposed monitoring system.

Table 1: Charatristics of sensors used in the experimentation.

Characteristic	Sensor Module			
	MQ2	**MQ7**	**MQ135**	**DTH-11**
Sensor Type	MOS	MOS	MOS	Negative temperature coefficient sensor
Target gas	Methane	Carbon monoxide	Carbon dioxide	Temperature and humidity
Typical detecton range	100-1000 ppm	10-10000 ppm	10-1000 ppm	20-90% RH 0-50°C
Accuracy	±5%	±5%	±5%	±5% RH ±2°C
Sensitive material	SnO_2	SnO_2	SnO_2	–
Senstvity	High	High	High	±0.7°C

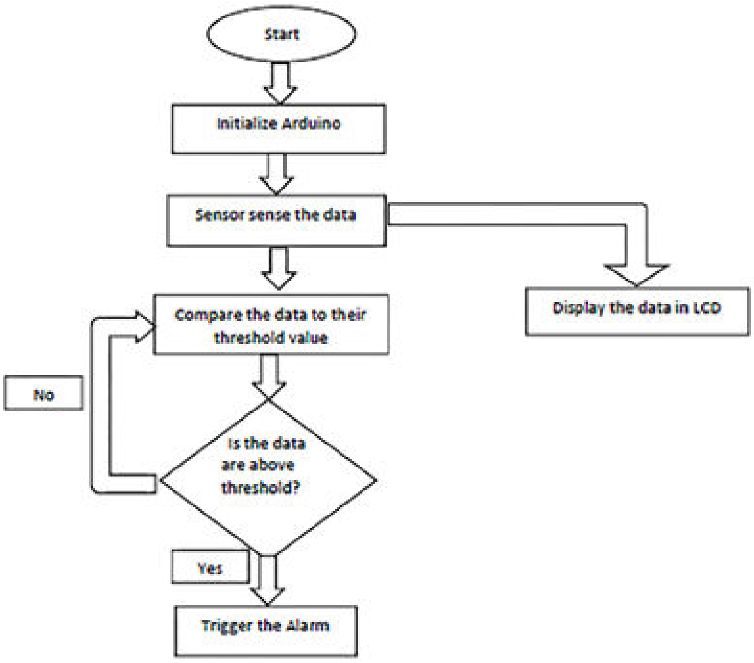


Figure 3: Flow chart of the gas monitoring system.

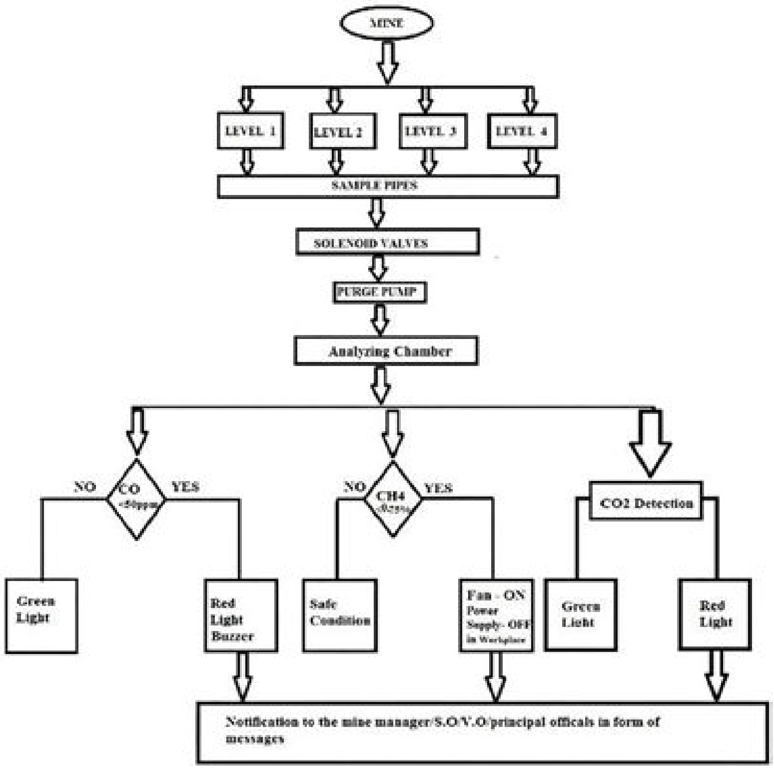


Figure 4: Operational characeristic of gas monitring sysem.

The automatic control unit is directly connected to the Arduino microcontroller, which automatically starts its work and controls the gasses when they exceed the preset value. The flowchart and block diagram of the entire gas monitoring system are shown in **Figure 3**, which shows the workflow of all four units. In addition, the operation of the gas analysis unit is shown in **Figure 4**, which provides a good overview of the overall operation of the gas monitoring system. Here you can find the construction details of the four main components of to take appropriate action in case of danger. **Figure 5** shows the electrical schematic of the gas analysis system. Here you can find the construction details of the four main components of the gas monitoring system, such as the suction unit, the analysis unit, the transmission unit and the automatic control unit. The suction unit collects sample air through the sample lines using a vacuum pump connected to a relay unit. The sample lines are powered by 12 volts DC. The analysis unit, which detects the presence of gasses, analyses the collected air samples and activates a warning signal when the gas concentration exceeds the allowable limit. The analysis chamber consists of three gas sensors, one temperature and one humidity sensor, such as MQ2, MQ7, MQ135 and DHT-11 sensor for the analysis of methane, carbon monoxide, carbon dioxide, air temperature and humidity respectively. The analogue pins of the sensors are connected to the antilog pins of the Arduino and the VCC and GND pins of the Arduino are used for power supply. The sensors transmit the data to the Arduino, which forwards the data to the control unit via the transmitter unit. Of all the sensors, most sensor modules are based on metal oxide (SnO2), which behaves well against volatile gasses. Therefore, they can be considered more reliable and efficient for gas monitoring. In addition, these sensors are suitable for both gas monitoring and temperature monitoring and provide a low cost and low-power solution that has no impact on the environment during its operation.

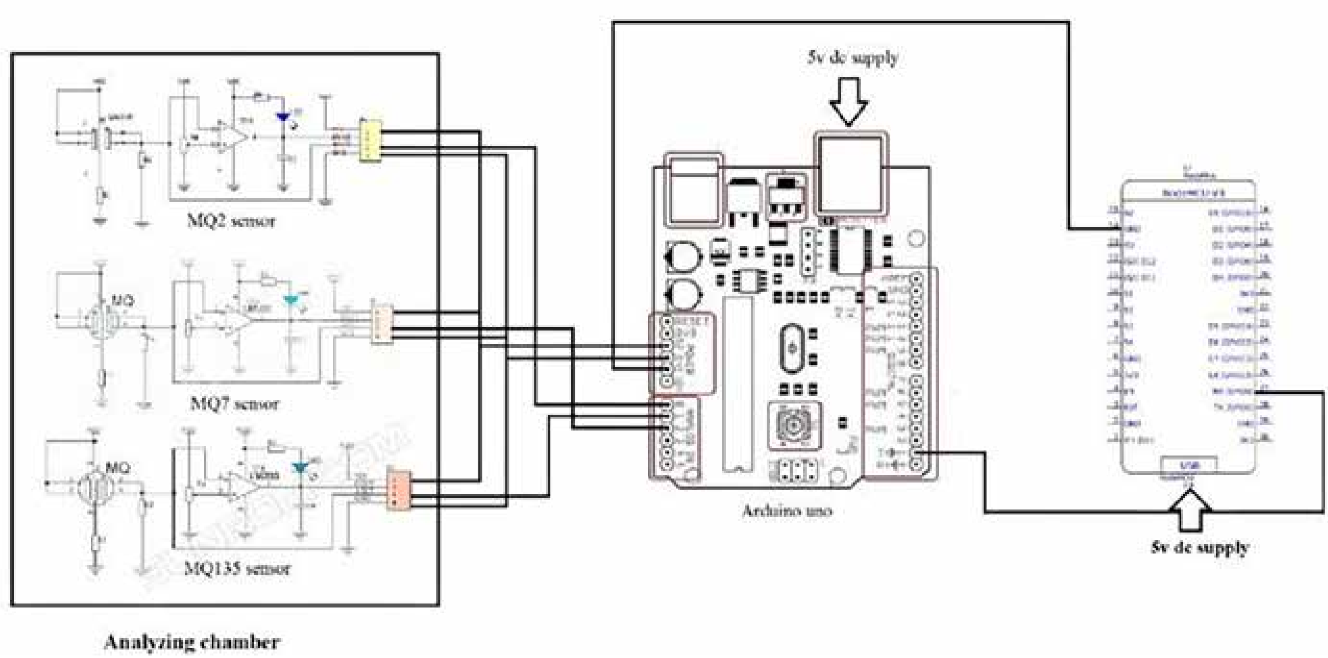


Figure 5: Circuit diagram of analysis unit.

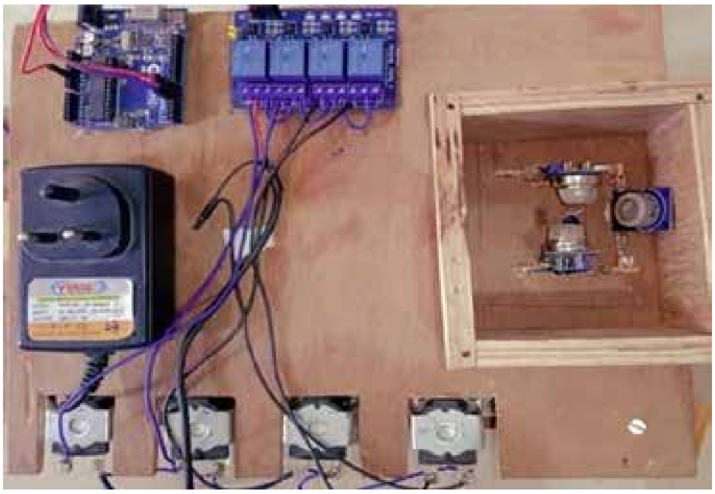


Figure 6: Photographic view of automatic gas monitoring system.

The transmission unit consists of the node MCU (i.e. microcontroller unit). It is used for data transmission from the Arduino to the Thing Speak over a wireless network, so that the analysed data can be forwarded to the relevant authorities to take appropriate action in case of danger. **Figure 5** shows the electrical schematic of the gas analysis system.

The sensor (in the analysis unit) transmits data via analogue pins to the Arduino, which passes it on to the node's MCU, as shown in **Figure 5**. In order for the sensors and serial communication to work properly, the code is passed to the Arduino using the Arduino IDE software. The construction of the automatic monitoring system was built on a wooden platform, whose photographic view can be seen in **Figure 6**.

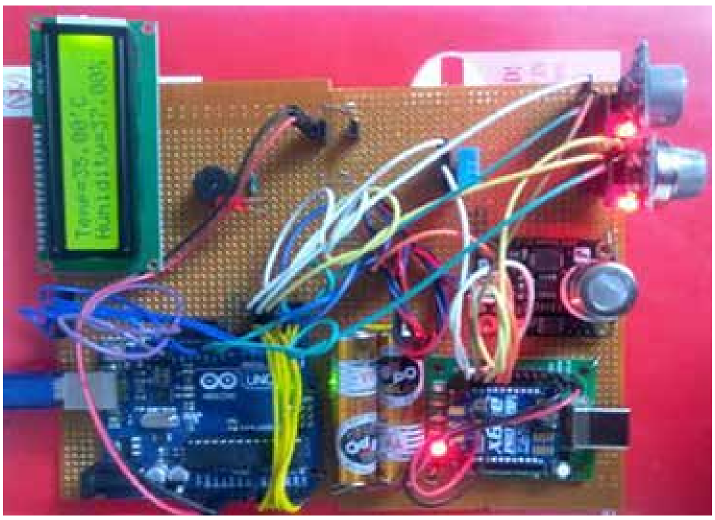


Figure 7: Photographic view of real time monitoring automatic system.

RESULTS AND DISCUSSION

To test the developed monitoring system under real-time conditions using a wireless sensor network, an experimental study is conducted in the laboratory. The experiments are conducted in such a way that it can measure the main gasses of underground coal mining. For a first implementation, we have designed the complete system on a breadboard, as shown in **Figure 7**.

This section deals exclusively with the experimental analysis of the developed IOT-based gas monitoring system. The developed gas monitoring system was tested in a laboratory in a closed chamber under controlled environmental conditions with varying gas level by changing the position of the sensor and controlling the valve gas sources (such as diesel engine and liquid gas cylinder). As mentioned earlier, the MQ2, MQ7 and MQ135 sensors were

Table 2: Comparison of readings of methane gas.

Sl. No.	As obtained by monioring system (PPM)	As obtained by multi gas detectr (PPM)
1	196	190
2	203	205
3	199	201
4	197	192
5	183	181
6	183	180
7	182	181
8	180	179

Table 3: Comparison of readings of carbon monoxide and carbon dioxide.

	Carbon Monoxide		Carbon dioxide	
Sl. No.	As obtained by monioring system (PPM)	As obtained by multi gas detectr (PPM)	As obtained by monioring system (PPM)	As obtained by multi gas detectr (PPM)
1	359	360	103	105
2	368	370	104	106
3	367	369	106	106
4	374	375	108	109
5	117	114	110	111
6	112	110	114	113
7	106	108	16	118
8	103	104	118	120

used for the detection of methane, carbon monoxide and carbon dioxide.

Readily available liquefied petroleum gas (LPG) was used for the methane gas and diesel engines were used to generate carbon monoxide and carbon dioxide. The concentration of the above gasses was also measured using a digital multi-gas detector (model: MSA ALTAIR 4XR). The measured values of the gas monitoring system and the multigas detector are presented in **Table 2** and **Table 3** for comparison. **Figure 8**. Monitoring of methane gas in real time **Figure 9**. Monitoring of carbon monoxide gas in real time **Figure 10**. Monitoring of air temperature and humidity in real time Readily available liquefied petroleum gas (LPG) was used for the methane gas and diesel engines were used to generate carbon monoxide and carbon dioxide. The concentration of the above gasses was also measured using a digital multi-gas detector (model: MSA ALTAIR 4XR). The measured values of the gas monitoring system and the multigas detector are As can be seen in **Table 2** and **Table 3**, the gas concentrations recorded by the gas monitoring system are very close to the values detected by the multigas detector. The same pattern can be seen in **Figure 8** and **Figure 9**. It can be concluded that the developed gas monitoring system is reliable and can be used in underground coal mines to monitor the mine environment.

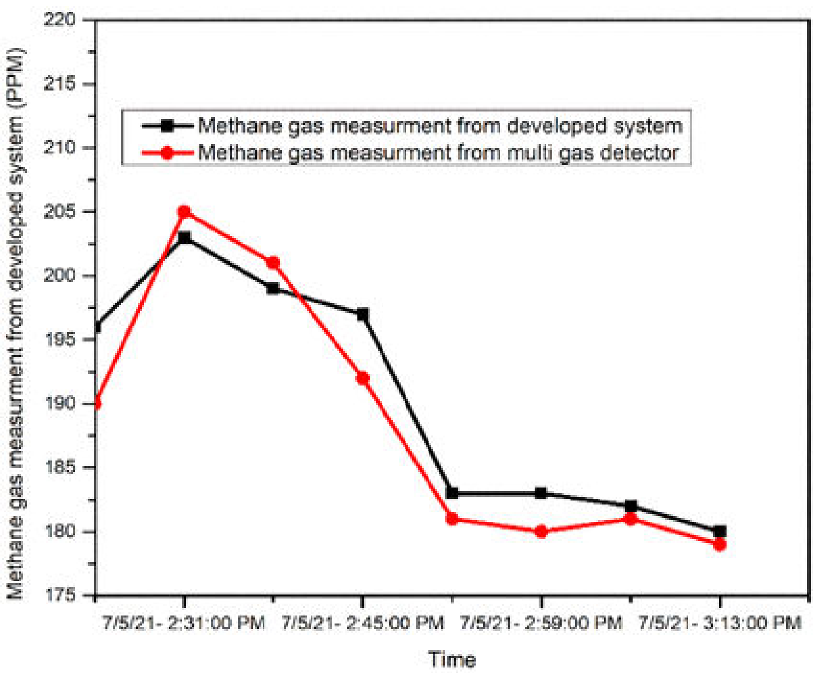


Figure 8: Monitoring of methane gas in real time

In order to measure the air temperature and relative humidity by the developed monitoring system eight different observations were recorded. The complete observation (for humidity and temperature measurement) was recorded with at different time (varying interval of 7 minute) and the observed readings are plotted against the time which can be seen from **Figure 10**. It can be observed that the measured reading from the developed model is capable of measuring the air temperature and humidity of the environment. This monitoring system will help in maintain the record of underground mines atmosphere in real time.

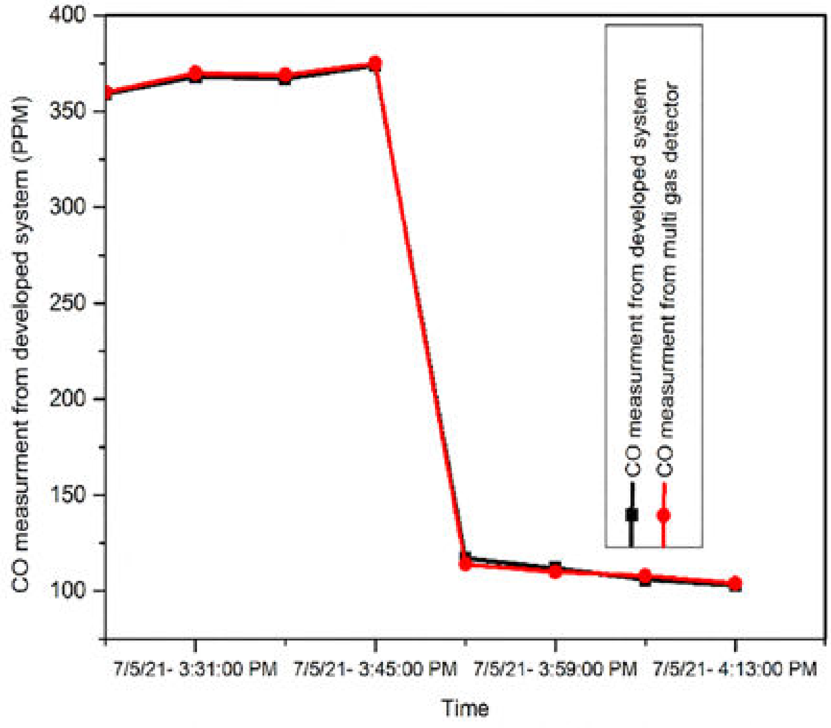


Figure 9: Monitoring of carbon monoxide gas in real time

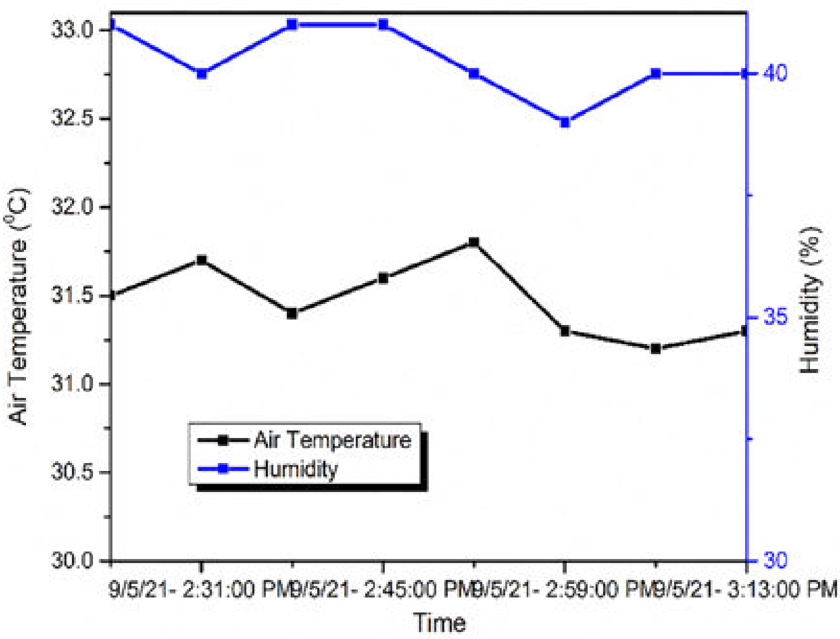


Figure 10: Monitoring of air temperature and humidity in real time

CONCLUSIONS

The safety of miners in underground coal mines is always at high risk. Miners must perform their work under the influence of many toxic and flammable mine gasses. In order to maintain the safety of people, machines and materials, it is necessary to detect future hazardous conditions in advance. This is where continuous monitoring and recording of the mine atmosphere could play an important role. This study provides a way to implement artificial intelligence in the rugged environment of underground coal mines. In this work, an IoT based gas, temperature, and humidity monitoring system was developed to assess atmospheric conditions in underground coal mines. The developed system consists of multiple metal oxide sensor modules for real-time monitoring of gasses, temperature, and humidity in underground mines. The monitored data can be transmitted via Wi-Fi to the relevant mine officials so that they can take appropriate precautionary measures in the event of an emergency. The developed IoT based monitoring system has been tested and validated in the laboratory for measuring carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), air temperature and humidity. While the monitoring results indicate accurate prediction, there are still some limitations in this study. These limitations include the harsh atmospheric conditions in underground mines (temperature and humidity effects) and the combined output of multisensory modules. In addition, this study only addressed the monitoring of five atmospheric parameters in underground mines and ignored the other parameters that may contribute to the changes in climate in underground mines.

ACKNOWLEDGMENT

Authors would like to thank the management of Aditya Engineering College, Surampalem for providing necessary support while conducting the present research work.

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From timber to technology: the evolution of ground control in mining

By Trevor Barratt MD *Mining & Quarry World / Coal International*

In the subterranean world of mining, few innovations have reshaped safety and productivity as profoundly as roof bolting. What began as a tentative experiment in the early 20th century has evolved into a sophisticated system of ground control, underpinning modern mining operations across the globe.

THE PRE-BOLTING ERA: TIMBER AND TRIAL

Before the advent of roof bolts, miners relied on timber props and cribbing to support underground roofs. While timbering was simple and accessible, it was also bulky, labour-intensive, and prone to failure under dynamic loads. Roof collapses were tragically common, and mechanization was hindered by the physical footprint of timber supports.

Australia followed suit, with Elrington Colliery pioneering bolting in 1949, and widespread adoption occurring by the 1980s. The UK's National Coal Board began trials in the 1950s, gradually integrating bolting into its underground operations.

ACTIVE VERSUS PASSIVE SUPPORT

Up to the 1980s in what was then a thriving UK coal industry owned by British Coal and indeed most underground mines worldwide the accepted method of supporting a roadway was to erect steelwork that was strutted and sometimes sheeted, lagged and backfilled.

This approach can be termed passive as it provided little or no assistance to the main body of the surrounding strata. In practise what happened is that the immediate strata break up and bulks, gradually filling the voids. As the strata fails the steelwork buckles and is gradually forced inwards. This type of support system is essentially one of damage limitation. Its outstanding advantage is that the support yields gradually, providing plenty of warning of failure. Unfortunately, it was also very expensive, difficult to transport and erect, and often required substantial back repair.

Roof bolting as a ground support method has roots going back much further than many people realise. Here's a quick timeline of its early development:

- **1872 – North Wales, UK** GB
  The earliest recorded use of bolts for rock reinforcement was in a slate quarry in North Wales.
- **1918 – Germany** DE
  A coal mine introduced bolts as a means of ground support.
- **1927 – United States** US
  Mechanical rock bolts were applied in a metal mine.

- **Late 1940s – US coal industry**
  The US Bureau of Mines began formal studies on bolting in 1947, and by 1948–49 roof bolting was being trialled in underground coal mines. Adoption was rapid — within two years, over 200 US coal mines were using the method.
  1949 – First roof bolter patent
  Anton Lobbert filed a patent for a dedicated roof bolting machine on August 17, 1949, published in 1953.
- By the early 1950s, roof bolting was replacing timber props in many mines, marking one of the fastest technology adoptions in coal mining history.
- mechanical bolts to today's fully encapsulated resin systems — it's a fascinating progression in both engineering and safety.

Strata reinforcement systems such as roof bolting offer a cheaper and safe alternative to passive support. These systems are commonly termed active as they work by reinforcing the rock so as to prevent it from failing in the first place.

Because the two approaches are fundamental mentally different, combining strong reinforcement with conventional roadway support is inappropriate and should be viewed as a transitional measure. Roof Bolting is most effective as a support system when used to reinforce intact Rock. It follows that its primary area of application should be in achieving fast, cheap drivage of trunk roadways, face headings and gate roadways for retreat faces, rather than in the broken rock surrounding the gates of advancing faces.

In a brief conclusion, roofbolting is a fundamentally different approach to roadway support than conventional steelwork and needs to be recognised as such. The two systems are not complimentary and if mixed, both must be designed as the primary support system. The benefits of roofbolting are such that, in a competitive environment of the type found in some mines worldwide, mines that do not roofbolt cannot compete. The transition from passive to active systems is now nearly universal, though legacy support types may still appear in regions with weaker enforcement or older infrastructure.

INTERNATIONAL EXPERIENCE

Since its widespread adoption in the mid-20th century, roof bolting has evolved significantly in both methodology and equipment. Early systems relied on simple mechanical anchors, but modern techniques now include:

- Resin-grouted bolts: These provide superior bonding and load transfer, especially in fractured or damp strata.

- Cable bolts: Used in situations requiring longer reinforcement lengths, such as high-span excavations or deep-seated competent rock layers.
- Pattern bolting: Strategic placement of bolts in grid formations to uniformly distribute stress and prevent localized failure.

These innovations have allowed roof bolting to adapt to a wider range of geological conditions, including soft rock formations and high-stress environments.

Since its widespread adoption advancements in roof bolting have been driven not just by technological innovation, but by international cross-pollination of best practices.

ENGINEERING EVOLUTION: FROM MECHANICAL TO RESIN

Early bolts were mechanical, relying on expansion shells to grip the rock. While effective in certain conditions, they were sensitive to installation errors and geological variability. The 1980s saw the rise of resin-grouted bolts, which offered superior anchorage and load distribution. These fully encapsulated systems became the industry standard worldwide, especially in hard rock environments.

Today, ground control engineers use advanced modelling tools like FLAC3D to simulate bolt behaviour, optimising patterns and tensioning for site-specific geology. Innovations such as friction bolts, cable bolts, and smart bolts with embedded sensors continue to push the boundaries of safety and efficiency.

REGULATION AND RESISTANCE

Despite its promise, roof bolting didn't immediately reduce fatalities. In fact, the 1960s–1970s saw a paradoxical rise in roof fall incidents, largely due to inconsistent installation and lack of standardized practices. Regulatory bodies like MSHA in the US and the HSE in the UK responded with stricter roof control plans, mandating engineering justification and periodic inspections.

Cultural resistance also played a role. Miners accustomed to timbering were sceptical of bolts, and early failures reinforced caution. Over time, however, training programs and performance data helped shift perceptions, cementing bolting as the cornerstone of modern ground control.

GLOBAL ADOPTION AND FUTURE FRONTIERS

Today, roof bolting is ubiquitous in underground coal mining, from the Appalachian Basin to the Bowen Basin. Countries like China, South Africa, and Poland have embraced international best practices, integrating bolting into mechanized mining standards.

Looking ahead, the future of ground control lies in real-time monitoring, AI-driven design, and sustainable materials. Smart bolts capable of transmitting stress data could revolutionize predictive maintenance, while biodegradable resins may reduce environmental impact.

GLOBAL TRENDS

- Many countries now use monitoring systems (e.g., extensometers and smart bolts) to assess roof integrity and adjust bolting strategies in real time.

- **International collaboration** — through bodies like the International Society for Rock Mechanics — has facilitated the spread of standards and exchange of research findings.

REGIONAL PRACTICES AND INFLUENCES

- **United States:** Relatively shallow depths and competent roof strata enabled early success with simple bolting systems. Their regulatory emphasis on routine roof inspection helped advance bolt-testing protocols that were later adopted internationally.

- **Australia:** High-stress ground conditions and financial pressure to reduce costs accelerated innovation. Automation and data-driven reinforcement design have become hallmarks of Australian mines.

- **South Africa:** Deep mining in Witwatersrand gold fields posed unique challenges — especially seismic activity. Yielding bolts and energy-absorbing systems emerged in response and influenced standards elsewhere.

- **India:** Increased reliance on roof bolting in coal and metal mines due to economic drivers and government investment in mechanized methods. However, variability in rock competence still limits standardization across regions.

- **Europe (e.g., Poland, Germany):** Transition from passive support to bolting was bolstered by EU-wide safety reforms. Emphasis was placed on controlling deformation early, leading to hybrid reinforcement approaches in some older mines.

- **International collaboration** — through bodies like the International Society for Rock Mechanics — has facilitated the spread of standards and exchange of research findings.

Trevor Barratt Managing Editor takes a look at some of the crucial requirements to be considered for the implementation of roof bolting and gives an insight of practises used in the 80s in British coalfields and indeed implemented worldwide.

A PRACTICAL DESIGN METHOD

A practical design method for roof bolting is absolutely critical—both for safety and for operational efficiency in underground mining. Here's why it matters so much:

- **Worker Safety First**
  Roof bolts are the primary defence against roof collapses. A well-designed system directly reduces the risk of ground falls, protecting lives and minimizing injuries.

- **Tailored to Geology**
  No two mines are alike. A practical method accounts for site-specific factors like rock type, stress conditions, and mining geometry. This ensures the bolts actually reinforce the ground effectively.

- **Cost Efficiency**
  Over-engineering wastes money; under-engineering invites disaster. A practical method helps strike the right balance—using just enough support to maintain safety without unnecessary expense.

- **Adaptability to Change**
  Mines evolve. A robust design method allows for adjustments as conditions shift—whether due to depth, excavation method, or unexpected geological features.

- **Quantifying Uncertainty**
  Probabilistic approaches recognize that input parameters (rock strength, bolt performance, etc.) vary naturally. This allows engineers to design for reliability, not just theoretical safety factors.

The .design approach must be two stage. The first stage creates an initial design which is derived from local experience supplemented by knowledge of the strata fabric and field stresses. The second stage is based on the monitoring scheme which provides the necessary information to optimise the design for the prevailing situation.

INITIAL DESIGN

Initially one needs to assess the strength of the surrounding rock strata and what forces are likely to be acting on it. One must also consider the intended purpose of the roadway.

FABRIC OF THE ROCK

Currently the ability to describe the surrounding strata is limited to a geological description, an estimate of its mechanical strength base on laboratory testing and an estimate of the frequency and orientation of joints and bedding planes.

The data is gathered from inspection of the roadway and from cored boreholes in the roof. Use of this information makes a first order estimate of the capabilities of the strata using a classification scheme.

FIELD STRESSES

The stresses acting on a roadway can be conveniently divided into;

1. Pre mining stresses
2. Interaction induced stresses caused by nearby workings.
3. Stresses caused by the current excavations.

PRE- MINING STRESSES

It is generally accepted that the pre- mining stresses are depth related. That is the deeper one goes the greater they are. Research conducted by the then British Coal in a UK coal mine in the 80s showed that they are not equal in all directions. The stresses at a point can be defined by three perpendicular principal stresses, one of which is usually vertical and the other two horizontal. Research has shown that in the horizontal plane the ratio of principal stresses can be as much as 2:1 The orientation of the maximum principal horizontal stress appears from the data gathered at the time to be reasonably consistent, trending NW-SE

INTERACTION INDUCED STRESSES

Variation in the stress field near a new drivage are caused by past and present mining activity, above, below and alongside. The qualitative effects of interaction stresses became well known to British mining engineers and further theoretical work has attempted to quantify some of these.

STRESSES INDUCED BY EXCAVATION

The stresses induced in the surrounding strata by a roadway drivage are related to the roadway size, shape and timing of support. A small roadway induces lower stresses in the surrounding strata than a large one. Similarly, the closer a roadway approaches a circular shape the more evenly will induced stresses be distributed.

INITIAL DESIGN IMPLICATIONS

The initial design should always be based on local experience. This should be supplemented by further information gained from an assessment of the fabric of the strata and an understanding of the effects of the field stresses on the surrounding strata.

Factors that must be considered are as follows:

1. Where possible face should be laid out such that gateroads are parallel to the maximum principal horizontal stress.

2 A denser bolting pattern will be required in roadways driven at right angles to the maximum principle horizontal stress then in those driven parallel to it.

3. A greater bolt density will be required on one side of the roadway driven at a high angle to the maximum to the maximum principle horizontal stress.

4. Where possible, advantage should be taken of stress relief effects above, below and beside old goafs. If necessary, horizontal stress relief can be obtained by pre-driving sacrificial headings nearby.

5. Adequate stable pillars should be left between adjacent faces to ensure that the strata is not overstressed.

6. Roadway width should be minimised. Buckling stresses in the beam increase in proportion to the square of its length.

In typical UK conditions, the strata are weak enough and field stresses are high enough for timing to be very important. It is usually necessary to ensure that the strata are reinforced close to the face and immediately after excavation.

The optimum roadway shape from a construction point of view is rectangular. If the strata are sufficiently weak or there are particularly high field stresses then it may be necessary to use an arch shaped profile, although this presents special problems for roof bolt installation.

MONITORING BASED DESIGN STAGE

The second design stage requires that monitoring be used to tune the initial design and attain the optimum and most cost-effective strata reinforcement system for the prevailing conditions this is the only approach which provides complete confidence.

The monitoring system required in most cases is neither complex nor expensive and can be installed without undue delay as part of the normal construction cycle. It comprises three measurements: roof dilation, roadway closure and roof bolt extension.

Roof dilation can be measured using four wires anchored by springs at different levels in a roof borehole, although more sophisticated multipoint extensometers may be required in very rapidly deforming roadways. Roadway closure is obtained using a tape measure or measuring pole with floor heave and roof lowering being distinguished either by the line stretched between rib anchors or by levelling.

Roof bolt extension is measured using an extensometer. This is a hollow roof bolt with a thin steel rod running through the annulus and welded to the bolt at its top end. The extension of the bolt at any time is given by the distance up the central hole of the end of the rod. An array of extensometer bolts should be installed across the heading at the monitoring station in place of the usual roofbolts

The purpose of this monitoring is to establish whether roof bolts are providing sufficient reinforcement to the roof strata to prevent roof dilation. information gained is sufficiently detailed to allow specific design recommendations to be made.

GLOBAL ADOPTION AND FUTURE FRONTIERS

Today, roof bolting is ubiquitous in underground coal mining, from the Appalachian Basin to the Bowen Basin. Countries like China, South Africa, and Poland have embraced international best practices, integrating bolting into mechanized mining standards.

Looking ahead, the future of ground control lies in real-time monitoring, AI-driven design, and sustainable materials. Smart bolts capable of transmitting stress data could revolutionize predictive maintenance, while biodegradable resins may reduce environmental impact.

CONCLUSION: A QUIET REVOLUTION

Roof bolting may lack the glamour of cutting-edge extraction technologies, but its impact is undeniable. It represents a quiet revolution—one that has saved lives, enabled mechanization, and transformed the very architecture of underground mining.

As we continue to dig deeper, both literally and figuratively, the story of ground control reminds us of that progress often begins with a bolt.

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Sustainable energy transition for the mining industry

The mining industry (MI), one of the largest energy consumers globally, is under increasing pressure to transition towards more sustainable energy systems. This paper explores the current trends in sustainable energy transition (SET) in mining operations, focusing on integrating renewable energy, decarbonisation efforts, economic and technological enablers, and sustainability frameworks. Through a systematic literature review utilising bibliometric tools such as Scopus and VOSviewer 1.6.20, this study identifies key themes, trends, and challenges shaping the future of energy transition in mining. Despite advancements in renewable technologies such as solar, wind, and hydrogen, the MI faces significant barriers, including high upfront costs, logistical challenges in remote operations, and inconsistent regional decarbonisation policies. The review highlights the importance of global regulatory alignment, technological innovation, and financial mechanisms to overcome these challenges and accelerate the industry's shift towards clean energy. Future research directions address gaps in renewable energy deployment, energy efficiency, and sustainability practices in the mining sector. This study aims to contribute to the academic discourse and provide actionable insights for industry stakeholders striving to achieve a SET.

The mining industry (MI) is pivotal in supporting global economies by providing essential raw materials for various sectors, including energy, manufacturing, and infrastructure. However, it is also one of the most energy-intensive industries, significantly contributing to global carbon emissions]. According to, the mining sector accounts for approximately 1.7 of the world's total energy demand, primarily driven by fossil-fuel consumption. This high energy demand, coupled with the industry's reliance on non-renewable energy sources, has drawn increased attention to the need for a sustainable energy transition (SET) within mining operations. As global climate change mitigation efforts intensify, transitioning to cleaner energy alternatives has become not only an environmental necessity but also a strategic imperative for the long-term sustainability of the industry.

SET in the mining sector encompasses the shift from conventional fossil fuels such as coal and diesel to renewable energy sources, including solar, wind, and hydrogen. This transition is crucial in aligning the MI with global decarbonisation goals, such as those outlined in the Paris Agreement, which aims to limit global temperature rise to below 2 °C. Researchers have highlighted that integrating renewable energy systems within mining operations can significantly reduce greenhouse gas emissions and improve energy security and long-term cost savings. For instance, studies by the World Bank Group suggest that adopting renewables in mining could reduce operational energy costs by up to 50% in specific remote mining locations, particularly when paired with energy storage solutions. Nevertheless, there is no comprehensive synthesis that exists on the application of suitable energy technologies in the mining sector.

Despite these advantages, the transition to sustainable energy in mining is fraught with challenges. High initial capital investment, logistical barriers, and the lack of a unified regulatory framework hinder the widespread adoption of renewable energy technologies in mining. Deploying renewable infrastructure in remote and off-grid mining locations, where access to the energy grid is limited, poses significant technical challenges. Additionally, the inconsistent implementation of decarbonisation policies across different regions further complicates the industry's ability to meet global emissions reduction targets; there is a need for more transparent global standards and more substantial governmental support to facilitate this energy transition, particularly in developing economies where mining remains a significant economic driver.

Our study aims to bridge the gap by systematically analysing existing studies to identify current challenges and propose solutions for SET in mining operations by analysing existing research via bibliometric analysis, highlighting the key themes and technological advancements that shape the future of mining energy systems. A thematic synthesis approach was used categorising findings into four key themes: renewable energy integration, decarbonisation and environmental policy, economic and technological enablers, and sustainability frameworks. By synthesising the latest developments and trends in these areas, this paper not only provides a detailed overview of the current landscape but also identifies critical research gaps and offers future research directions. These insights aim to advance academic understanding and practical solutions to accelerate the SET within the MI.

The layout of this paper follows. Having motivated the need for this review in Section 1, Section 2 describes the research methodology. Section 3 divulges the results of the bibliometric and trend analyses of the extant literature, and Section 4 discusses these results and offers insights. Section 5 gives future research pathways, and Section 6 concludes. This study reviews the current state of SET in the MI, points out gaps, and offers future research pathways.

2. RESEARCH METHODOLOGY

This research study undertakes a comprehensive literature review focusing on the SET in the MI. Advanced bibliometric tools such as Scopus and VOSviewer (version 1.6.20) have been employed to systematically search, identify, and analyse relevant academic contributions. Scopus was the preferred database because of its wide range of authentic publications compared to Google Scholar, Science Direct, and Web of Science. This study utilises Scopus due to its broad coverage of high-impact journals, particularly in engineering, sustainability, and operational research. It provides structured metadata, citation analysis, and advanced filtering options essential for bibliometric studies. While Web of Science and Google Scholar offer extensive databases, Scopus ensures consistency in data extraction and citation tracking and a pervasive coverage of journals specialising in mining. VOSviewer, a science mapping tool for producing, visualising, and exploring bibliometric networks and content analysis, was utilised for the scientometric analysis. An effective literature review requires a clear methodology to ensure rigorous and structured analysis. The literature review acknowledges potential biases, including selection bias due to thematic relevance, search strategy limitations that may exclude non-English or gray literature, and publication bias favouring significant findings. Efforts were made to ensure consistent data synthesis; however, differences in study designs and the tendency to underreport unsuccessful results may have introduced interpretation and reporting biases. Consequently, in line with PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analysis) guidelines, this study adopts the methodical, three-phase review approach illustrated in **Figure 1**. The PRISMA 2020 Main Checklist is appended as a Supplementary Material and the details of the review stages follow.

2.1. Stage 1: Identification of Studies

In the first stage, relevant studies were identified from Scopus using predefined search criteria and keywords related to SETs and mining. The selected keywords were included after several adjustments on Scopus ("sustainable energy" OR "renewable energy" OR "solar energy" OR "fossil fuel alternatives" OR "wind energy" OR "hydrogen" OR "electrification") AND ("MI" OR "mining engineering" OR "mining sector" OR "mineral extraction" OR "resource extraction" OR "mineral production" OR "mining operations"). A total of 2359 records were retrieved from this search on 11 January 2025. At this stage, no records were removed due to duplication, automation exclusions, or other technical reasons, ensuring all retrieved studies underwent the screening process.

2.2. Stage 2: Screening of Studies

The screening stage involved a thorough review to assess eligibility based on predefined exclusion criteria. The initial 2359 records were screened, and reports were sought

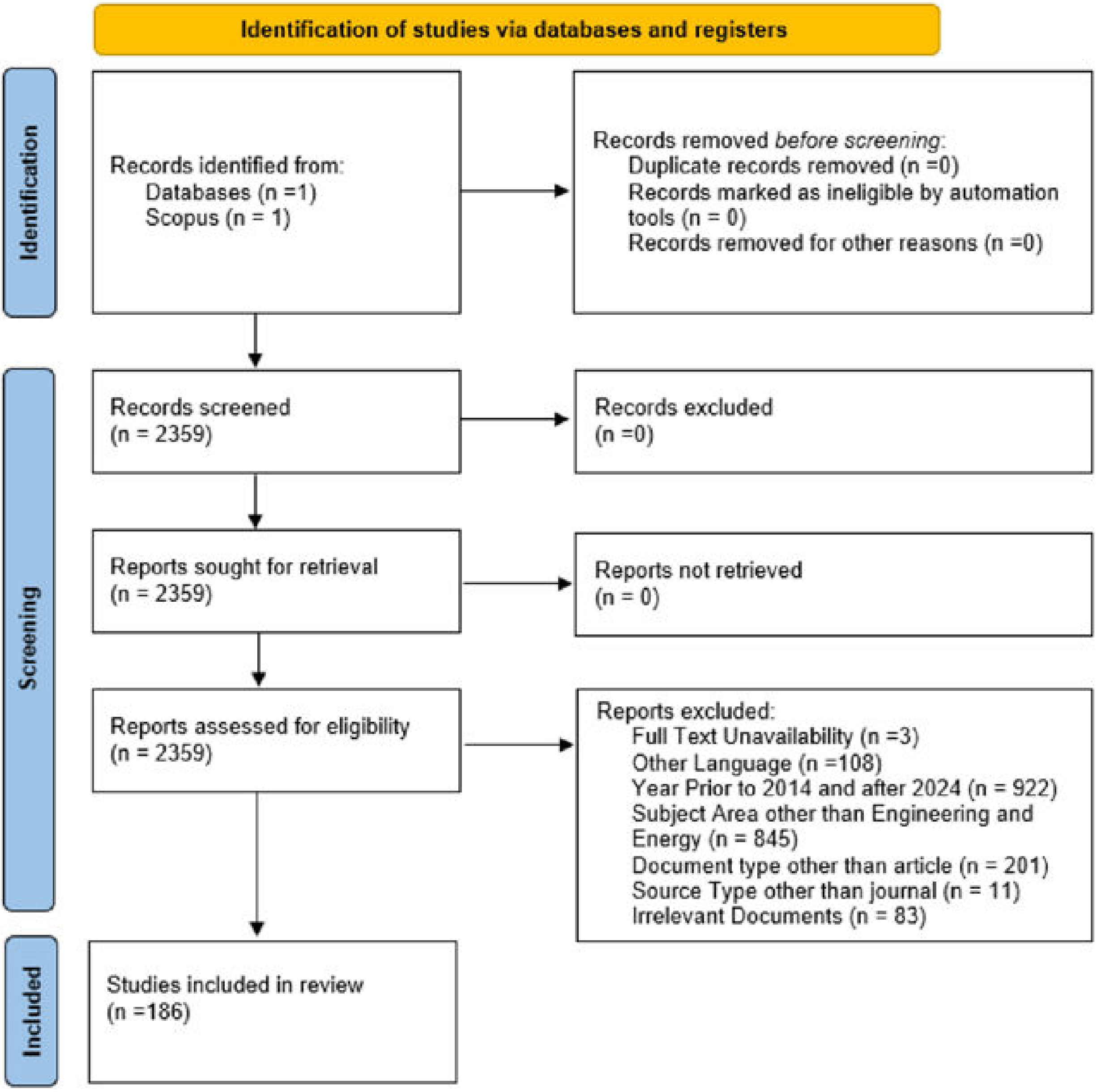

Figure 1: PRISMA flow diagram for this review.

for retrieval without exclusions at this point. After further assessment, studies were excluded for reasons such as full-text unavailability (3), language other than English (108), publication dates outside the 2014–2024 range (922), subject areas unrelated to engineering and energy (845), document types other than journal articles (201), non-journal sources (11), and studies deemed irrelevant based on content (83). After applying these filters, 186 studies remained eligible for further manual analysis. The authors independently screened those eligible papers to ensure consistency through cross-validation and to resolve any discrepancies.

2.3. Stage 3: Inclusion of Studies

In the final stage, the remaining 186 studies were included for qualitative analysis and scientometric evaluation. The selected studies underwent detailed examination to identify knowledge gaps, technological trends, and future research directions in SET for mining operations. VOSviewer was used to visualise research networks and identify key themes. The study's structured approach, as summarised in **Figure 1**, ensured a robust synthesis of the existing literature. The 11 most influential studies, detailed in the next section, provided critical insights into the research landscape, guiding the discussion on technological advancements and areas requiring further exploration.

3. RESULTS

This section details the findings of the bibliometric analysis of the publications related to SET in the MI.

3.1. Publication Sources

Table 1 highlights the top 16 journals contributing to research on sustainable energy transitions in mining, based on an analysis of 186 papers using VOSviewer. The minimum document threshold was set to 3, yielding 16 sources. *Energies* leads with 19 documents and 200 citations, achieving a citation score of 6.2 in 2023, demonstrating its pivotal role in the field. *Journal of Cleaner Production* follows with 10 documents, and a significantly higher citation count of 290, reflecting its influence with a citation score of 13.7.

Table 1. Key publication sources for energy and sustainability research**.**

No	Journal	Documents	Citations	Total Link Strength	Citation Score (2023)
1	*Energies*	19	200	0	6.2
2	*Journal of Cleaner Production*	10	290	0	13.7
3	*International Journal of Hydrogen Energy*	8	130	0	10.6
4	*Sustainability*	8	51	0	4.9
5	*Energy Conversion and Management*	4	57	0	14.6
6	*Energy Research and Social Science*	4	86	0	10.9
7	*Mining Report*	4	2	0	_
8	*Renewable and Sustainable Energy Reviews*	4	158	0	22.6
9	*Energy*	3	82	0	12.7
10	*Energy for Sustainable Development*	3	5	0	7
11	*Energy Policy*	3	88	0	10.4
12	*IEEE Access*	3	8	0	9.8
13	*Journal of Mines, Metals and Fuels*	3	0	0	0.1
14	*Minerals Engineering*	3	15	0	12.1
15	*Recent Advances in Electrical and Electronic Engineering*	3	3	0	1.7
16	*Transportation Research Record*	3	4	0	3.2

Prominent energy-focused journals such as *Energy Conversion and Management* and *Renewable and Sustainable Energy Reviews* also appear, boasting high citation scores of 14.6 and 22.6, respectively. Notably, *Mining Report* has low citation activity, indicating limited influence in this domain. Although *Transportation Research Record* and *Recent Advances in Electrical and Electronic Engineering* contribute, their lower citation scores suggest niche relevance. This analysis underscores the dominance of interdisciplinary journals in shaping future research on energy transitions in mining, with a strong emphasis on sustainability and innovation.

3.2. Country, Co-Author, and Keyword Analyses

Figure 2 and **Table 2** present the global contributions of 28 countries to sustainable energy transition research in mining based on a VOSviewer (version 1.6.20) analysis of 50 countries. In **Figure 2**, the country co-authorship network colours represent regional research collaborations, with green indicating European partnerships, blue showing North American influence, and red highlighting Asian research networks. Yellow reflects Australia-Japan linkages, while purple (Indonesia) suggests isolated research efforts with minimal global connections. The visualisation shows strong intra-regional cooperation, with Europe and North America closely linked, while Asia connects globally but maintains internal research clusters.

For analysis in **Table 2**, the minimum document threshold was set to three, and 28 countries met this criterion. The data reveal that China (29 documents, 779 citations) and the United States (33 documents, 600 citations) lead in research output and influence. These nations' high citation counts, and substantial total link strengths (six and nine, respectively) indicate their central roles in shaping global research collaborations.

Australia (15 documents, 355 citations) and India (21 documents, 436 citations) also demonstrate significant contributions, reflecting their active engagement in the

Figure 2: Country co-authorship analysis.

Table 2: Total link strength of key countries of SET in mining research.

No.	Country	Number of Documents	Number of Citations	Total Link Strength
1	United States	33	600	9
2	China	29	779	6
3	India	21	436	5
4	Australia	15	355	11
5	Canada	15	165	8
6	Germany	10	143	7
7	Poland	9	79	6
8	South Korea	9	380	11
9	United Kingdom	7	123	7
10	Chile	6	140	5
11	Denmark	6	182	11
12	Iran	5	95	4
13	Malaysia	5	88	3
14	Sweden	5	134	6
15	France	4	96	5
16	Indonesia	4	6	3
17	Japan	4	80	1
18	Norway	4	245	6
19	South Africa	4	64	0
20	Brazil	3	31	8
21	Greece	3	73	0
22	Italy	3	11	1
23	Peru	3	13	0
24	Qatar	3	31	3
25	Russian Federation	3	63	0
26	Saudi Arabia	3	29	3

field. South Korea stands out with nine documents and 380 citations, supported by a high total link strength of 11, indicating strong international partnerships. In contrast, countries such as Indonesia (four documents, six citations) and Greece (three documents, 73 citations) show limited research influence and connectivity. **Figure 2** visually captures these research clusters and highlights the potential for strengthening global collaboration to advance sustainable energy transitions in mining.

The analysis of global contributions to sustainable energy transition research in mining underscores the prominence of leading nations like China, the United States, Australia, and India in driving research output and fostering collaborations. The network visualisation in **Figure 2** and data in **Table 2** highlight strong research clusters, particularly in Europe and Asia, while also revealing underrepresented regions such as Indonesia and Greece. These findings emphasise the need for broader international cooperation to bridge existing gaps and enhance knowledge exchange. Strengthening global partnerships can play a pivotal role in addressing the complex challenges associated with sustainable energy transitions in the mining sector.

3.3. Keyword Trend Analysis

Figure 3 provides a comprehensive overview of the co-occurrence of key terms in sustainable energy transition research for the mining sector. Out of 2762 keywords, the minimum occurrence threshold was set to seven, resulting in 52 keywords meeting the criterion. General terms like "article" were excluded to ensure the analysis focused on relevant technical terms. The network reveals distinct thematic clusters, with terms such as "renewable energies" (33 occurrences, 33.00 total link strength) and "renewable energy resources" (28 occurrences, 28.00 total link strength) forming a central research theme. This indicates a strong emphasis on renewable energy integration, with related terms like "solar energy" (22 occurrences) and "wind power" (15 occurrences) highlighting the growing interest in sustainable energy sources.

The colours in the author keyword co-occurrence network (**Figure 3**) represent distinct research themes in SET within the mining sector. Blue signifies research on renewable energy integration in mining operations, including terms such as "renewable energies," "sustainable development," "mining industry," and "climate change." This cluster highlights broad discussions on energy transition, the role of mining in sustainability, and the shift from fossil fuels to cleaner energy sources. Green represents renewable energy resources and policy, covering keywords like "renewable energy resources," "solar energy," "microgrid," "energy management," and "electric power transmission." This cluster suggests research focused on technological applications, regulatory policies, and infrastructure needed to facilitate the adoption of renewable energy in mining.

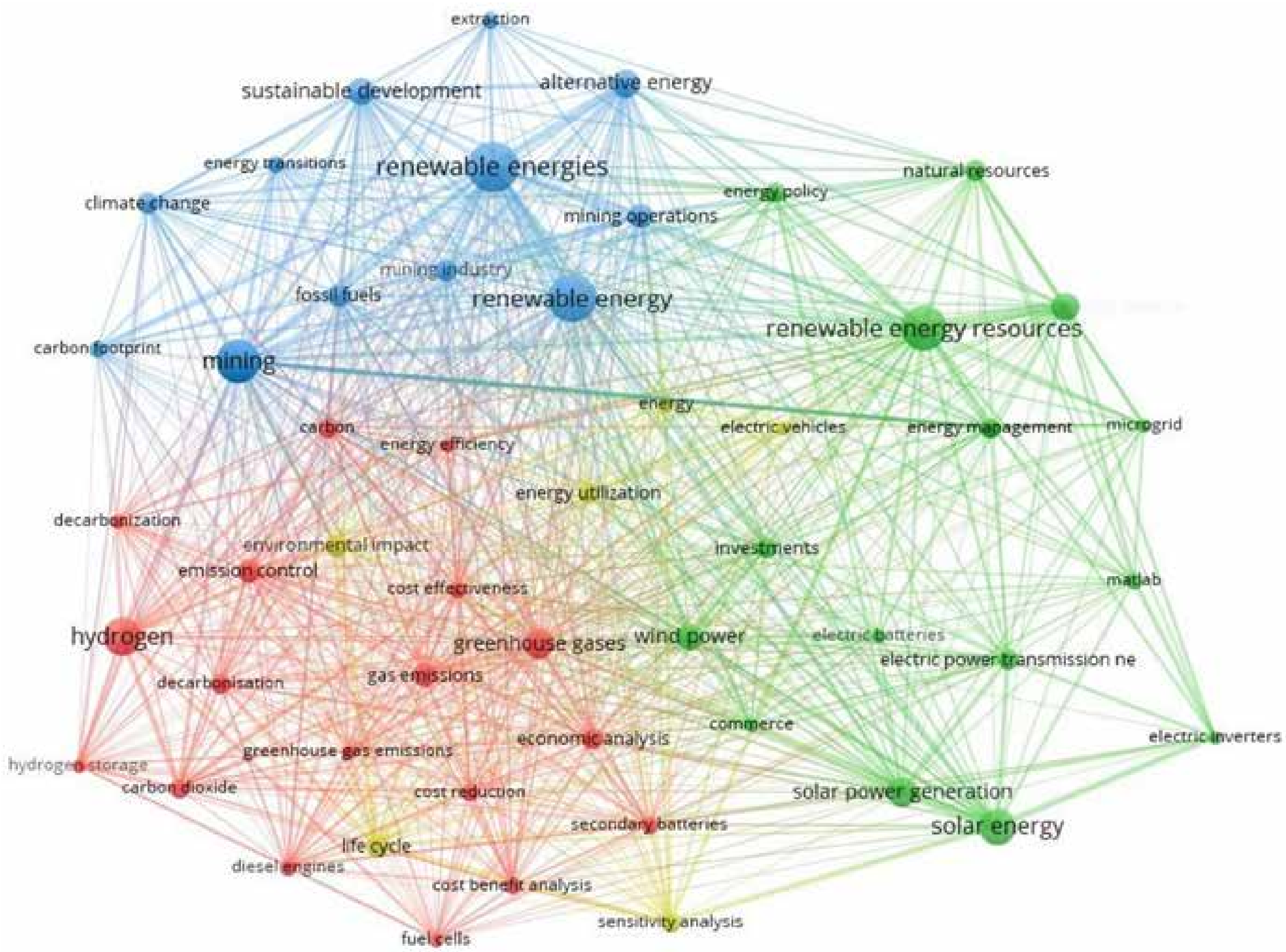

Figure 3: Author keywords analysis.

The red cluster centres on decarbonisation and emissions reduction, with key terms like "hydrogen," "carbon dioxide," "decarbonisation," "emission control," and "fuel cells." This area of research explores alternative fuels, carbon capture, and sustainable energy storage solutions. Yellow, on the other hand, highlights economic analysis and operational efficiency, containing terms such as "economic analysis," "cost-benefit analysis," "secondary batteries," and "energy utilisation." This cluster emphasises financial feasibility, investment considerations, and cost-reduction strategies for implementing sustainable energy solutions. The strong interconnections between these clusters indicate the interdisciplinary nature of sustainable energy transition research, where economic feasibility (yellow) links to decarbonisation (red), while energy policies (green) support the broader transition of mining operations (blue).

The "mining" theme is represented by terms such as "mining" (25 occurrences, 24.00 link strength), "mining industry" (12 occurrences), and "mining operations" (13 occurrences), demonstrating a significant focus on sustainable mining practices. The presence of keywords like "sustainable development" (15 occurrences) and "environmental impact" (12 occurrences) further underscores the industry's commitment to balancing operational efficiency with environmental stewardship. The "hydrogen" cluster also stands out, with "hydrogen" appearing 23 times and linked to terms such as "decarbonisation" (7 occurrences) and "emission control" (12 occurrences), emphasising the role of hydrogen technologies in achieving decarbonisation goals.

The total link strength values reflect the degree of interconnectedness between keywords. For example, "greenhouse gases" (17 occurrences, 17.00 link strength) and "carbon footprint" (eight occurrences, 7.00 link strength) demonstrate a strong association with discussions on emissions reduction and life-cycle assessments ("life cycle" with 12 occurrences). In contrast, terms like "secondary batteries" (eight occurrences) and "economic analysis" (11 occurrences) indicate emerging yet relatively underexplored research areas. Keywords such as "cost reduction" (eight occurrences) and "cost–benefit analysis" (eight occurrences) highlight a growing recognition of the need for economic feasibility studies alongside technical innovations.

This keyword analysis reveals that renewable energy, mining operations, and hydrogen-related technologies are central themes in sustainable energy transition research. High link strengths for terms like "renewable energy resources" and "mining" reflect their foundational roles in the discourse, while the prominence of "decarbonisation" and "emission control" underscores the industry's focus on reducing environmental impacts. However, underexplored areas like "secondary batteries" and "sensitivity analysis"

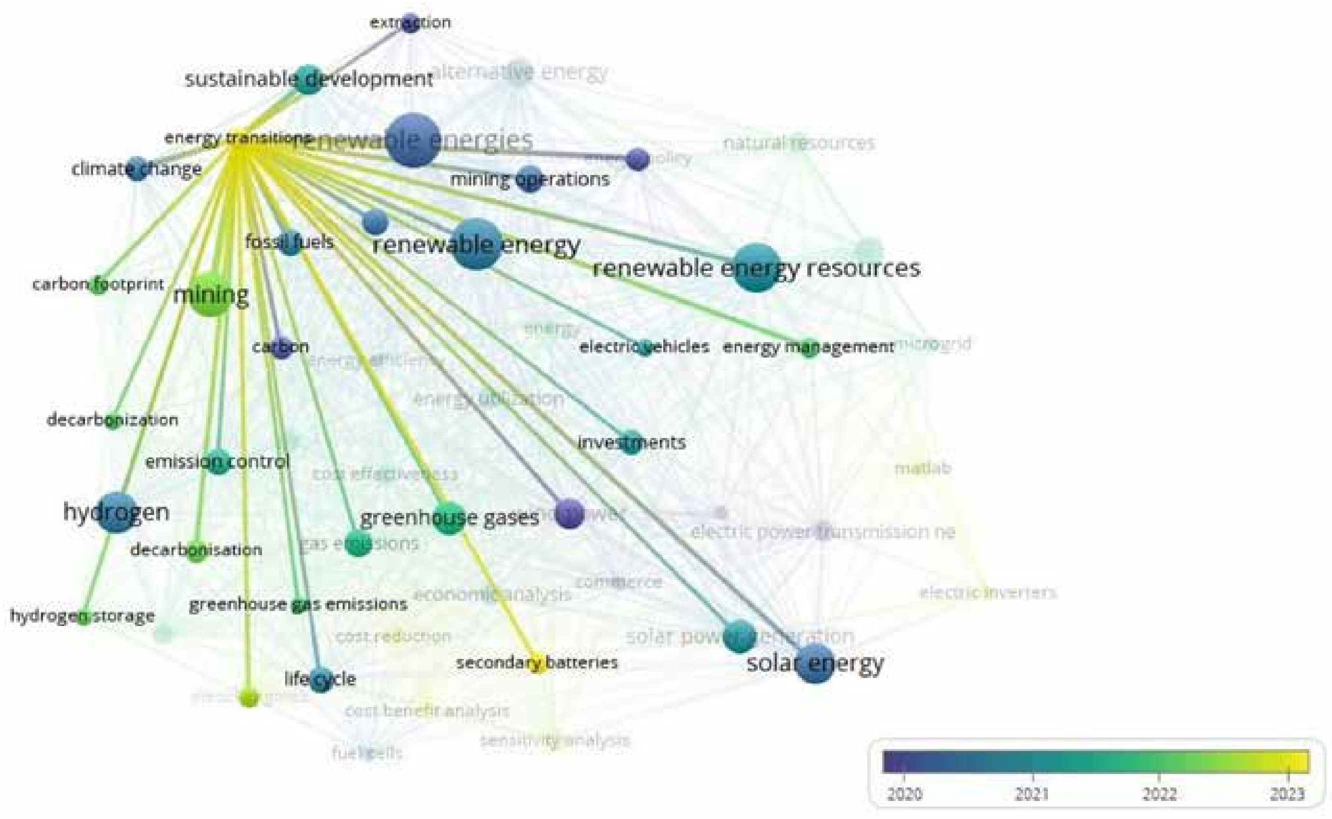

Figure 4: Network trends overlay visualization.

suggest opportunities for future research to enhance decision-making frameworks and improve energy storage solutions. By identifying these patterns, this analysis contributes to a deeper understanding of the research landscape and highlights potential pathways for advancing sustainable energy practices in the mining sector.

The overlay visualisation in **Figure 4** presents the temporal progression of research keywords related to sustainable energy transitions in mining, spanning the years 2020 to 2023. The colour gradient, ranging from purple (older studies) to yellow (recent research), provides insights into evolving research trends. The prominence of “renewable energies” (yellow) and its strong connections with terms like “solar energy,” “renewable energy resources,” and “energy policy” indicates an increasing focus on renewable energy implementation and policy frameworks in recent studies.

Older keywords, such as “mining,” “sustainable development,” and “climate change” (depicted in darker shades), reflect foundational research areas that have maintained relevance over time. Meanwhile, emerging terms like “hydrogen,” “decarbonisation,” and “emission control” in lighter shades signify the growing interest in decarbonisation technologies. The connection between “hydrogen” and “carbon dioxide” highlights efforts to address greenhouse gas emissions through innovative energy solutions.

Recent research has also expanded into topics like “electric vehicles,” “microgrids,” and “energy utilisation,” suggesting a shift toward integrating decentralised energy systems and improving energy efficiency in mining operations. The overlay visualisation reveals a dynamic research landscape, where earlier discussions on sustainability and climate action have evolved into more specialised studies on renewable technologies, economic feasibility (“cost-benefit analysis” and “investments”), and life-cycle assessments (“carbon footprint” and “life cycle”).

This trend analysis underscores the rapid expansion of interdisciplinary research, highlighting the importance of aligning sustainable energy solutions with both operational efficiency and environmental impact mitigation. The overlay also suggests future research directions, including optimising secondary energy storage (“secondary batteries”) and further exploring grid integration through “electric power transmission networks.” These insights pave the way for advancing sustainable energy transitions in the mining industry.

The 2014-2024 period was chosen to capture a decade of research, ensuring a balanced view of past developments and emerging trends in mining transitions. This approach helps identify long-term patterns, technological shifts, and policy changes. While recent research is vital, a broader time-frame provides deeper insights into the industry’s evolving sustainability efforts. Although the broader period 2014-2024 was initially considered, bibliometric analysis revealed that the most significant shifts in sustainable energy transition research in mining occurred between 2020 and 2023. Earlier studies were primarily policy-driven with limited technological applications, whereas recent research increasingly explores implementation-focused strategies.

The comparative analysis of research trends in sustainable energy transition (SET) in mining (**Table 3**) highlights the evolution of research focus from broad sustainability

Table 3: Comparative analysis of research trends in SET in mining (2020-2023).

Period	Research Focus	Notable Keywords	Implications
2020-2021	High-level discussions on sustainability and climate change impacts, broad renewable energy policies	"Sustainable development", "climate change", "renewable energies", "fossil fuels", "carbon footprint", "mining"	Foundational research setting the stage for energy transition discussions but lacking specific technological applications.
2021-2022	Shift towards targeted renewable energy applications, focus on energy efficiency, microgrids, and electric vehicle integration	"Renewable energy", "solar energy", "energy management", "electric vehicles", "greenhouse gases", "emission control"	Increased focus on operational sustainability, addressing emissions reduction and integration of sustainable technologies into mining.
2022-2023	Emphasis on applied technological solutions, hydrogen energy, and decarbonization strategies	"Hydrogen", "decarbonization", "hydrogen storage", "secondary batteries", "solar power generation", "cost-benefit analysis"	Stronger industry shift towards practical solutions for carbon neutrality, energy storage, and economic viability of sustainable mining operations.

themes to specialised energy solutions. Initially, research between 2020 and 2021 emphasised high-level discussions on sustainability, climate change, and renewable energy policies; this is reflected visually in **Figure 4** as the blue and turquoise circles While the environmental impact of mining was a key concern, studies lacked a strong focus on specific renewable energy technologies or practical applications.

From 2021 to 2022, the research shifted towards more targeted renewable energy applications. Studies increasingly explored solar energy, energy efficiency, microgrid integration, and electric vehicle adoption in mining operations. The growing emphasis on reducing greenhouse gas emissions and carbon footprints reflected a heightened interest in quantifying the environmental benefits of sustainable energy transitions. This period also saw the emergence of energy management and grid integration studies, indicating a move towards operational sustainability.

The most recent trends from 2022 to 2023 emphasise applied technological solutions, with hydrogen energy and decarbonisation becoming central themes, as shown in yellow in **Figure 4**, signalling 2023. Research has increasingly focused on hydrogen storage, secondary batteries, and emission control strategies, reflecting efforts toward long-term carbon neutrality. Additionally, studies linking solar power generation with economic viability through cost reduction and cost–benefit analysis indicate a growing recognition of the financial implications of sustainable energy in mining. **Table 3** below encapsulates these shifts, demonstrating how research has evolved from conceptual frameworks to implementation-focused strategies.

Table 4 exhibits a comprehensive summary of recent and influential research studies focusing on sustainable operational efficiency in mining, with a particular emphasis on renewable energy adoption, environmental monitoring, and process optimisation. The studies analysed cover various technological advancements, such as the implementation of hybrid energy systems, renewable resource management, and innovative solutions for mine rehabilitation. For instance, explores rare earth element (REE) recovery from mining tailings using low-energy systems, demonstrating the potential to support mine rehabilitation. Several studies, such as, delve into the decarbonisation of gold mining by integrating renewable energy sources, showing a significant reduction in CO_2 emissions. These findings emphasise the growing shift toward net-zero goals through strategic energy transitions and innovative energy recovery methods.

Despite the promising results, **Table 4** also outlines limitations that require further exploration, such as high capital costs, policy enforcement gaps, and performance issues in varying environmental conditions. Notably, underscores the potential of hybrid hydrogen and wind systems in remote cold-climate mines but highlights the need for more case studies in diverse climatic conditions. Collectively, the studies in **Table 4** provide valuable insights into the pathways for achieving sustainable mining operations through technological innovation and strategic resource planning.

The qualitative analysis employed thematic analysis to assess the 186 articles, focusing on relevance, citation impact, and journal ranking. The 11 most influential studies, highlighted in **Table 4**, were selected for their critical insights into technological advancements and research gaps. These studies guided discussions on emerging trends and helped identify areas needing further exploration, ensuring a comprehensive and impactful analysis of the research landscape.

4. DISCUSSION

Following the scientometric analysis of the bibliometric characteristics of SET in the MI, the in-depth qualitative discussion shifted towards summarising emerging themes related to energy transition in mining, identifying existing research gaps, and proposing a comprehensive framework by linking current research topics to potential future directions.

4.1. Key Themes Identified for SET in the MI

This section describes the key themes of SET in the MI, including core principles and methodologies for evaluating existing studies and strategies for addressing the challenges and opportunities in the transition process. The discussion will explore how renewable energy integration (core principle), decarbonisation and environmental responsibility (performance evaluation), economic and technological enablers (operational considerations), and sustainability frameworks and policy alignment (strategic

Table 4: Summary of influential studies on sustainable mining and renewable energy integration.

Author	Year	Title	Research Objectives	Findings	Limitations	Conclusion	Future Research
Levett *et al.*	2024	Water-soluble Rare Earth Elements (REEs) Recovered from Uranium Tailings	Analyze rare earth element recovery for mine rehabilitation.	REE recovery demonstrated using low-energy systems in rehabilitation.	Scaling requires hydrology and stability studies.	REE recovery supports mine rehabilitation with green technologies.	Develop large-scale solar-assisted leaching systems.
Trench *et al.*	2024	Gold Production and the Global Energy Transition – A Perspective	Achieve net-zero emissions in gold production with energy transition.	Gold mining with renewables reduces CO_2 emissions by 78%.	Supply chain decarbonization remains partial.	Net-zero goals are feasible with integrated renewables.	Certify carbon-neutral gold supply chains.
Velický	2023	Renewable Energy Transition Facilitated by Bitcoin	Examine Bitcoin mining's impact on balancing renewable energy grids.	Bitcoin mining stabilizes energy grids using surplus renewable energy.	Environmental impacts of mining energy usage remain high.	Bitcoin mining can function as a dynamic load to reduce curtailment.	Research green consensus algorithms for mining.
Marín *et al.*	2023	Design for Sustainability: An Integrated Pumped Hydro Reverse Osmosis System to Supply Water and Energy for Mining Operations	Explore the viability of hydro-reverse osmosis for mine water management.	Hydro-reverse osmosis reduced mine water costs and GHG emissions.	High initial costs for implementation.	Hydro-reverse osmosis systems are feasible for remote sites.	Reduce capital costs of hydro-reverse osmosis units.
Pouresmaieli *et al.*	2023	Integration of Renewable Energy and Sustainable Development with Strategic Planning in the Mining Industry	Develop strategic frameworks for renewable energy in mining.	Renewables reduced costs and decarbonised mining supply chains.	Gaps in policy enforcement impact outcomes.	Strategic renewables lower supply chain costs and emissions.	Deploy energy storage to stabilise mining grids.
Kalantari and Ghoreishi-Madiseh	2022	Hybrid Renewable Hydrogen Energy Solution for Remote Cold-Climate Mines	Evaluate hydrogen and wind integration for decarbonizing open-pit mines.	Cost reduction and full decarbonisation achieved with hybrid systems.	Limited climate case studies.	Hybrid systems show cost-effective potential for mine decarbonisation.	Optimise configurations for varying wind levels.
Igogo *et al.*	2021	Integrating Renewable Energy into Mining Operations: Opportunities, Challenges, and Enabling Approaches.	Assess renewable energy integration challenges and opportunities in mining.	Renewable adoption reduces costs and improves community engagement.	High capital costs and regulatory challenges.	Renewables can enhance sustainability and reduce GHG emissions.	Implement regulatory frameworks for renewables.
Quiñones *et al.*	2020	Analyzing the Potential for Solar Thermal Energy Utilization in the Chilean Copper Mining Industry	Quantify solar thermal energy's feasibility in Chilean copper mining.	Solar thermal energy provided up to 30% of heat demand in mining.	Strong dependence on solar irradiance levels.	Solar thermal systems can replace a significant amount of fossil fuels.	Study thermal energy storage for large-scale integration.
Imasiku and Thomas	2020	The Mining and Technology Industries as Catalysts for Sustainable Energy Development	Quantify energy efficiency and GHG reduction in copper mining operations.	Improved refining efficiency and electrification can halve energy use.	Does not assess all stakeholder energy inputs.	Industrial collaborations can improve copper extraction efficiency.	Promote tech-driven knowledge-sharing partnerships.
Kuyuk *et al.*	2019	Designing a Large-scale Lake Cooling System for an Ultra-deep Mine: A Canadian Case Study	Study mine exhaust heat recovery for renewable energy.	Waste heat recovery enhanced site sustainability with minimal costs.	Requires high heat-to-energy conversion ratios.	Heat recovery improves energy self-sufficiency in remote mines.	Optimize thermal conductivity in mine recovery systems.
Pamparana *et al.*	2017	Integrating Photovoltaic Solar Energy and a Battery Energy Storage System to Operate a Semi-autogenous Grinding Mill	Optimize SAG mill energy using PV-BESS systems.	PV-BESS systems improved mill efficiency and reduced emissions.	No data on system reliability during cloudy periods.	PV-BESS systems lower operational emissions and costs.	Assess seasonal impacts on energy storage performance.

considerations) can be optimised to bridge gaps and drive future innovations in mining.

Renewable Energy Integration. Renewable energy integration focuses on replacing traditional fossil fuel-based energy sources with renewable alternatives such as solar, wind, and hydrogen in mining operations. This transition is a core principle of sustainable energy practices, aiming to reduce the environmental footprint of the mining sector while ensuring operational efficiency. Renewable energy sources offer the potential to significantly cut down greenhouse gas emissions, reduce reliance on non-renewable resources, and contribute to a more sustainable mining process. Integrating these technologies is vital for meeting global sustainability goals and minimising the negative environmental impact of mining. The challenges of integrating renewable energy into mining include the high initial costs, variability in energy supply, and the need for energy storage solutions. Mining sites often operate in remote locations, which presents logistical challenges in deploying large-scale solar farms or wind turbines. However, technological advances such as energy storage systems and hybrid solutions (e.g., combining solar with traditional energy sources) offer promising opportunities to overcome these hurdles and ensure a stable energy supply for mining operations. Renewable energy integration also provides long-term economic benefits, as it can reduce energy costs over time, especially as the cost of renewable energy technologies continues to decrease. Moreover, companies that invest in renewable energy improve their environmental performance and align with stricter regulations, enhancing their corporate social responsibility profile. Integrating renewable energy is a fundamental step toward a more sustainable and economically viable future for the MI.

Decarbonisation and Environmental Policy. Decarbonisation in the MI refers to reducing carbon emissions across all mining activities, from exploration to extraction and processing. This theme emphasises the MI's responsibility to minimise environmental impact and aligns with global efforts to combat climate change. Environmental policies and regulations, such as carbon taxes and emissions caps, are increasingly pushing mining companies to adopt low-carbon technologies and practices. Decarbonisation is essential not only for reducing the carbon footprint of mining but also for maintaining compliance with international sustainability standards. Implementing decarbonisation strategies requires a multi-faceted approach, including the adoption of cleaner energy sources, improving energy efficiency, and utilising carbon capture technologies and the scope within which the decarbonisation is aimed. Mining companies are exploring innovative solutions, such as the electrification of machinery and vehicles, transitioning from diesel-powered equipment to electric alternatives, and adopting smart technologies to optimise energy usage. Decarbonisation efforts in the mining industry vary significantly across regions, with developing countries facing unique challenges in policy enforcement, financial constraints, and fossil-fuel dependency. In South Africa, policies like the Renewable Energy Independent Power Producer Procurement Program (REI4P) and self-generation incentives have led to increased adoption of solar and wind energy in mining, as seen in Gold Fields' South Deep Mine, which reduced carbon emissions by 110,000 tons annually. However, inadequate grid infrastructure limits further expansion. Chile has adopted a carbon tax (USD 5 per ton of CO_2) and a green hydrogen strategy, allowing firms like BHP's Escondida Mine to transition to 100% renewable energy by 2025 and reducing CO_2 emissions by three million tons annually, but prohibitive costs and limited hydrogen production remain barriers. India is focusing on the electrification of mining fleets under FAME-II and renewable energy incentives, enabling Tata Steel's Joda East Mine to integrate electric dump trucks, reducing fuel costs by 30%, though weak EV infrastructure and coal dependence persist. In contrast, Indonesia's Carbon Economic Value (CEV) policy introduced a carbon trading mechanism, but fossil-fuel subsidies continue to limit impact, with mining companies like Vale Indonesia turning to hydropower for nickel mining and cutting 200,000 tons of CO_2 annually, yet coal-fired power plants still dominate the sector. These cases highlight the divergence in decarbonisation approaches: where Chile and South Africa lead in renewable integration, India focuses on electrification, and Indonesia struggles with policy enforcement. A harmonised international strategy, supported by climate finance, technology transfer, and hybrid energy models, could accelerate mining decarbonisation across developing economies.

These efforts are evaluated based on their ability to reduce emissions, improve efficiency, and contribute to long-term environmental sustainability. Environmental policies play a critical role in driving the decarbonisation agenda within the MI. Governments are increasingly introducing stringent regulations that require mining companies to disclose their carbon emissions and set targets for reduction; companies that fail to comply face penalties and reputational damage. Conversely, those that successfully implement decarbonisation strategies not only contribute to a cleaner environment but also gain a competitive advantage in the marketplace by aligning with the growing demand for sustainable practices.

Economic and Technological Enablers. Economic and technological enablers refer to the financial and technical aspects that facilitate the energy transition in mining. The excessive cost of implementing renewable energy systems, upgrading existing infrastructure, and adopting innovative technologies can be a significant barrier for mining companies. However, innovative financing models, such as green bonds, government incentives, and public–private partnerships, are emerging as solutions to support the energy transition. Economic considerations must balance the initial investment costs with long-term savings from lower energy consumption and reduced emissions. Economic enablers play a crucial role in accelerating the transition to sustainable energy in mining, particularly through the declining cost of renewable energy technologies and supportive financial mechanisms. The levelised cost of energy (LCOE) for solar and wind power has significantly decreased, making these alternatives more financially viable for mining operations, especially in remote areas. Additionally, carbon pricing mechanisms, government subsidies, and tax incentives have encouraged mining companies to adopt low-carbon technologies. A notable example is BHP's Nickel West project in Australia, which has integrated a 100 MW solar farm and battery storage to power its operations, significantly reducing reliance on fossil fuels. Similarly, Gold Fields' Agnew Gold Mine became the first Australian mine to be powered by a hybrid renewable microgrid comprising wind, solar, battery storage, and gas backup, leading to a 50% reduction in carbon emissions and operational cost savings. These economic incentives reduce financial barriers, making sustainability an increasingly cost-effective option for the mining industry. On the technological side, advancements in energy storage, smart grids, and digital mining solutions are critical enablers of SET. Technologies like hydrogen fuel cells, electrification of mining equipment, and artificial intelligence (AI)-driven optimisation tools can help improve energy efficiency and reduce operational costs. For example, AI can help monitor and predict energy usage, allowing companies to reduce waste and improve energy management across operations. These technologies also enable the MI to meet regulatory standards more efficiently. Economic and technological enablers reduce the cost of transitioning to sustainable energy and provide a competitive edge by improving operational efficiency. Companies that leverage the latest technologies and financial mechanisms can optimise their energy consumption, lower emissions, and reduce operating costs over time. As these technologies evolve and become more affordable, they will continue to play a crucial role in enabling a smooth and cost-effective energy transition in the mining sector. Technological advancements are also crucial enablers of this transition, with innovations in hydrogen energy, battery storage, and digitalised energy management systems reshaping mining operations. The deployment of hydrogen-powered haul trucks, such as the NuGen Zero Emission Haulage Solution by Anglo American, is a prime example, demonstrating the feasibility of replacing diesel fleets with hydrogen fuel cell electric vehicles (FCEVs). This initiative, first implemented at the Mogalakwena Platinum Mine in South Africa, is expected to cut diesel consumption by one million litres annually, significantly reducing carbon emissions. Another significant technological enabler is the Rio Tinto Gudai-Darri Mine in Western Australia, which integrates solar energy, autonomous haulage, and AI-driven energy optimisation systems to enhance operational efficiency and sustainability. Furthermore, blockchain-based energy trading platforms, such as those evaluated by Glencore and BHP, are being explored to enhance transparency and efficiency in renewable energy procurement and carbon credit trading. These advancements highlight the growing role of technology-driven energy solutions in the decarbonisation of mining operations.

Sustainability Framework. A sustainability framework provides a strategic approach to integrating sustainable practices throughout the MI's operations. This framework incorporates key aspects such as environmental stewardship, social responsibility, and economic viability, ensuring that mining activities align with global sustainability goals. The framework helps guide the industry's transition to cleaner energy by setting clear goals, defining best practices, and establishing accountability measures. Sustainability frameworks often include life-cycle assessments (LCAs) to evaluate the environmental impact of mining operations from start to finish. LCAs are a critical tool within the sustainability framework, as they provide a comprehensive view of the environmental impact of mining activities. By evaluating all stages, from resource extraction to waste disposal, LCAs help mining companies identify areas where improvements can be made, such as reducing water usage, improving waste management, and minimising energy consumption. The sustainability framework also promotes the circular economy concept by encouraging the recycling of materials and reducing waste in mining operations. A key example of sustainability integration can be observed in the complex mining approach proposed by, where traditional mining operations are transitioning towards multi-product production that aligns with Environmental, Social, and Governance (ESG) principles. Their study highlights how integrating water desalination, methane utilisation, and secondary raw material recovery within coal mining operations not only enhances sustainability but also ensures economic viability by repurposing waste into valuable by-products. This multi-resource utilisation model demonstrates how mining companies can leverage sustainable technologies to reduce environmental footprints while creating additional revenue streams. Furthermore, Bondarenko *et al*. emphasise the necessity of incorporating alternative energy sources, such as low-potential thermal energy from mine groundwater, to support circularity in mining operations. These insights reinforce the sustainability framework's role in facilitating the industry's shift towards resource-efficient and resilient mining models.

The success of a sustainability framework depends on the alignment of company policies with local and international regulations, as well as stakeholder engagement. Mining companies must collaborate with governments, communities, and other stakeholders to ensure that sustainability goals are achieved. By incorporating sustainability into the core of their operations, mining companies protect the environment and enhance their reputation, ensure regulatory compliance, and create long-term economic value. We note that the ESG framework has been extensively examined in the context of mining sustainability, addressing environmental, social, and governance factors. However, to achieve a more holistic and inclusive approach, ESG has been extended to the QBL – Quadruple Bottom Line by incorporating cultural sustainability. This expansion recognises the critical role of cultural heritage, local traditions, and Indigenous knowledge in shaping sustainable mining practices, ensuring that technological advancements align with societal values and long-term community well-being. In alignment with the QBL framework, cultural sustainability plays a vital role in the long-term success of mining operations. Culture encompasses the values, practices, and traditions of the communities where mining takes place, and respecting these cultural dimensions is essential for maintaining positive relationships with local stakeholders. Cultural sustainability involves ensuring that mining practices do not disrupt the social fabric of communities or erode their cultural heritage. This includes promoting Indigenous knowledge systems, protecting sacred sites, and engaging in culturally appropriate consultation processes. By integrating cultural considerations into their sustainability frameworks, mining companies not only foster goodwill but also build resilience in operations by enhancing community trust and collaboration. Including culture within the QBL emphasises businesses' broader responsibilities to preserve social identity and local customs, which are integral to achieving a truly sustainable and inclusive circulatory in the MI.

Limited Adoption of Renewable Energy Technologies. The adoption of renewable energy technologies in the MI remains limited due to several factors despite their critical role in SET. Renewable technologies such as solar, wind, and hydrogen power offer substantial benefits in reducing carbon emissions and lowering reliance on fossil fuels. However, the initial investment costs for setting up renewable energy infrastructure, especially in remote mining locations, are high. Additionally, mining sites may face logistical challenges, such as a lack of proximity to renewable energy grids or rugged terrain for installing solar farms or wind turbines. These barriers create a significant gap in the widespread implementation of renewable energy technologies in mining. To address this gap, mining companies must explore hybrid energy solutions combining renewable energy with traditional power sources to ensure reliable energy supply in remote locations. Governments and investors also need to provide financial incentives and support to reduce the capital burden on mining companies. In addition, advances in renewable technology and energy storage solutions can help make these technologies more accessible and cost-effective. Closing this gap will allow the MI to reduce its environmental impact and make significant strides towards sustainability.

Inconsistent Decarbonisation Efforts Across Regions. While global climate goals require a unified approach, decarbonisation efforts across the MI are inconsistent, primarily due to varying regulatory frameworks and regional economic conditions. In some countries, mining companies face strict environmental policies that enforce emissions caps and require sustainability reporting, pushing them towards adopting low-carbon technologies. In other regions, however, the absence of such stringent regulations or the economic reliance on fossil fuels results in less urgency for decarbonisation. This regional disparity creates a significant gap in the MI's collective ability to reduce carbon emissions on a global scale. To close this gap, there needs to be a harmonised approach to decarbonisation, with international bodies advocating for stronger, unified environmental policies. Cross-border collaboration, where mining companies share the best practices and technologies, could help level the playing field and encourage more widespread adoption of decarbonisation strategies. Moreover, governments in lagging regions should offer incentives or subsidies to promote cleaner mining operations, ensuring that all regions contribute equally to global decarbonisation efforts.

Technological Gaps in Energy Efficiency and Smart Solutions. Although energy-efficient technologies like AI-driven energy optimisation tools, hydrogen fuel cells, and electrified mining equipment offer tremendous potential, a gap remains in their widespread application in the MI. Many mining companies, notably smaller or less technologically advanced ones, do not have access to the infrastructure or expertise needed to implement these technologies. This gap slows the potential improvements in energy efficiency that could reduce operational costs and environmental impact. Without advanced technological solutions, mining operations continue to rely on traditional, less efficient methods, contributing to higher carbon emissions and energy waste. Closing this technological gap requires investment in research and development to create more affordable, accessible, and scalable energy-efficient technologies. Governments and international organisations should also encourage technology transfers, providing mining companies with the tools and expertise they need to modernise their operations. Collaboration between tech companies, governments, and the mining sector will be crucial in closing this gap and driving innovation to ensure that energy-efficient technologies become standard in mining operations across the globe.

Economic Barriers to Large-Scale Implementation. Economic barriers remain a significant challenge in implementing the MI's renewable energy and sustainability initiatives. The upfront costs associated with transitioning to renewable energy infrastructure, deploying advanced technologies, or complying with decarbonisation policies can be prohibitive, especially for smaller mining companies. Additionally, the return on investment for renewable energy projects may take several years to materialise, making them less attractive to companies with limited financial flexibility. This gap hinders the widespread adoption of sustainability initiatives, as companies may prioritise short-term cost savings over long-term environmental and operational benefits. To address these economic barriers, governments and financial institutions should offer more attractive funding mechanisms, such as green bonds, subsidies, or low-interest loans, to encourage investments in sustainable energy projects. Public–private partnerships can also be critical in reducing financial risks and sharing the burden of initial investments. Moreover, as renewable energy technologies continue to decrease in cost and global regulations become stricter on carbon emissions, the economic case for sustainability will strengthen, encouraging more companies to invest in energy transition initiatives. By addressing these economic barriers, the MI can accelerate its path towards sustainability while maintaining financial viability.

4.2. Bridging the Circularity Gap in SET in the MI

Bridging the circularity gaps for SET in the MI requires targeted strategies across key areas. To enhance renewable energy integration, governments and financial institutions should provide more substantial incentives, such as tax breaks and subsidies, to offset the high initial capital costs of renewable energy projects. Public–private partnerships can share risks and benefits, making it easier for mining companies to adopt clean energy technologies like solar, wind, and hydrogen. Additionally, developing scalable renewable energy solutions tailored to remote mining locations can help overcome logistical barriers and facilitate widespread adoption in the industry.

Decarbonisation efforts must be globally standardised to ensure consistency across regions. International regulatory bodies should establish unified decarbonisation standards and carbon pricing mechanisms for the mining sector. For example, a relevant case study is Poland, which has implemented the EU Emissions Trading System (ETS) to regulate carbon emissions, particularly in its coal-dependent mining sector. Despite being subject to carbon pricing, Poland's mining industry has faced challenges in transitioning to cleaner energy due to economic dependency on coal and slow adoption of renewables. Some mining companies have begun investing in carbon capture and storage (CCS) and renewable energy integration, but policy inconsistencies and financial constraints have limited large-scale implementation. While carbon pricing has increased operational costs, it has also driven companies to explore low-emission technologies to maintain competitiveness. However, Poland's reliance on coal-fired power continues to hinder full decarbonisation, requiring stronger policy enforcement and incentives to accelerate sustainable mining transitions. Creating platforms for knowledge sharing on low-carbon technologies and emissions reduction best practices would further drive global adoption of decarbonisation strategies. Investment in technology transfer and innovation is essential for closing the technological gap. Governments and industry leaders must invest in R&D to develop affordable, scalable solutions such as AI-powered systems, energy-efficient equipment, and advanced energy storage technologies. Facilitating access to these technologies through industry-wide collaboration and technology hubs will accelerate their adoption.

In addressing the economic barriers, diversified funding mechanisms such as green bonds, sustainability-linked loans, and carbon credit markets should be expanded to support mining companies in financing large-scale sustainability initiatives. Long-term sustainability funds and low-interest loans for energy transition projects would alleviate the financial burden on mining companies, especially smaller firms. Clear metrics for calculating long-term savings from renewable energy projects would also help companies better understand the financial benefits of transitioning to sustainable energy, encouraging broader investment in these initiatives. By addressing these gaps through a combination of financial, technological, and regulatory solutions, the MI can achieve a successful SET.

5. FUTURE RESEARCH PATHWAYS

Based on the literature and key theme analysis in the preceding sections, we identify and delineate future research directions (see **Figure 5**) to foster the ongoing transition towards sustainable energy and environmentally responsible practices within the MI.

5.1. Advancements in Renewable Energy Technologies for Remote Mining Operations

Future research should focus on developing scalable, cost-effective renewable energy solutions specifically designed for remote and off-grid mining sites. This includes hybrid systems that combine solar, wind, and hydrogen technologies with reliable energy storage systems. Investigating the feasibility of integrating smart grids or microgrids to manage energy distribution and consumption efficiently at these remote sites could also be a key area of study. Additionally, exploring ways to reduce the deployment costs of these technologies through innovative financing models and modular designs would support widespread adoption in the mining sector.

5.2. Global Decarbonisation Policies and Their Impact on Mining Operations

A significant future research direction involves studying the effects of harmonised global decarbonisation policies on the MI. This research could assess how different regions implement decarbonisation strategies and measure global

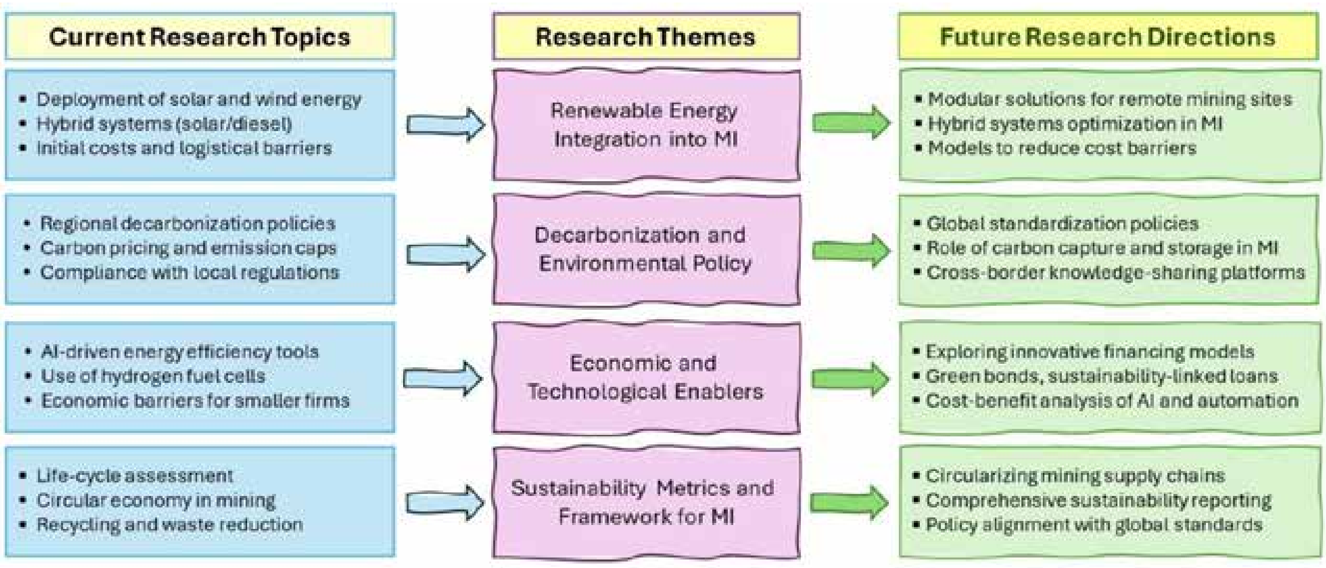

Figure 5: Framing future research directions for SET in MI.

carbon pricing mechanisms or emissions standards' economic, environmental, and operational impacts. A relevant case study is Poland, which has implemented the EU Emissions Trading System (ETS) to regulate carbon emissions, particularly in its coal-dependent mining sector. Despite being subject to carbon pricing, Poland's mining industry has faced challenges in transitioning to cleaner energy due to economic dependency on coal and slow adoption of renewables. Some mining companies have begun investing in carbon capture and storage (CCS) and renewable energy integration, but policy inconsistencies and financial constraints have limited large-scale implementation. While carbon pricing has increased operational costs, it has also driven companies to explore low-emission technologies to maintain competitiveness. However, Poland's reliance on coal-fired power continues to hinder full decarbonisation, requiring stronger policy enforcement and incentives to accelerate sustainable mining transitions. Research can also explore the interplay between local regulations and international agreements, identifying pathways for mining companies to comply with and benefit from uniform decarbonisation frameworks. The role of carbon capture and storage technologies in meeting decarbonisation goals could also be a focus of further study.

5.3. Technological Innovation for Energy Efficiency and AI Integration in Mining Operations

Research should delve deeper into developing and applying energy-efficient technologies and artificial intelligence (AI) tools to optimise energy use in mining operations. Future studies could investigate how AI-driven monitoring systems, machine learning algorithms, and autonomous equipment can enhance the efficiency of renewable energy utilisation and reduce overall energy consumption. The use of AI to predict energy demand, automate decision-making processes, and improve the accuracy of sustainability reporting could also be explored. Furthermore, research on the economic viability of these technologies, particularly for small- and medium-sized mining companies, would provide valuable insights into their scalability.

5.4. Sustainability Frameworks and Life-Cycle Assessments for Circular Mining Practices

Further research could explore the development of comprehensive sustainability frameworks tailored to the MI, integrating LCAs and circular economy principles. This includes evaluating the environmental impacts of mining operations from exploration to waste management, focusing on minimising resource extraction, and promoting recycling and reuse within the supply chain. It would also be quite valuable to investigate how mining companies can align with global sustainability standards, such as the United Nations Sustainable Development Goals (SDGs), and how they can measure and report on their progress toward these goals. Additionally, research on incorporating circular economy practices into mining operations could lead to more sustainable and efficient resource use.

6. CONCLUDING REMARKS

SET in the MI represents a pivotal shift that is critical for reducing the sector's environmental impact and essential for securing its long-term viability in an increasingly carbon-conscious global economy. This comprehensive review has highlighted the vital role of renewable energy integration, decarbonisation efforts, economic and technological enablers, and sustainability frameworks in driving this transition. While considerable progress has been made, particularly in adopting technologies such as solar, wind, and hydrogen energy, several key challenges remain, including the high initial costs of renewable energy infrastructure, logistical difficulties in remote mining locations, and inconsistent decarbonisation policies across different regions.

Addressing these barriers will require a coordinated approach involving governments, industry stakeholders, and the research community. Stronger regulatory frameworks, innovative financing models such as green bonds, and advances in energy-efficient technologies will be crucial in accelerating the adoption of clean energy solutions in mining operations. Furthermore, harmonising global decarbonisation policies and technological innovations like AI-driven energy management and energy storage systems will enable mining companies to achieve greater operational efficiency while reducing their carbon footprint.

In conclusion, SET in mining is not just an environmental necessity but a strategic opportunity for the industry to align with global sustainability goals, improve cost efficiencies, and enhance its competitive edge in the future. By continuing to innovate, collaborate, and invest in sustainable energy practices, the MI can lead global efforts to combat climate change and create a more resilient, sustainable future for generations to come.

AUTHORS

A. Akofa Amegboleza and M. Ali Ülkü

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Between coal and atoms

On the banks of the Bengawan Solo River, villagers still recount harvests measured by the rise and fall of water. One day, that same river could cool a small modular reactor, sending power to the Java-Bali grid. The leap from irrigation canals to nuclear turbines captures the paradox of Indonesia's path – a nation rooted in agrarian memory yet propelled toward industrial destiny. Indonesia cannot hope to reach its eight percent growth ambition by 2029 with coal and gas alone. Today, the country operates about 90 gigawatts (GW) of installed capacity, with nearly 50 GW fired by coal and less than one-fifth from renewables. The state utility's new plan, the 2025–2034 RUPTL, envisions 69.5 GW of additional capacity, three-quarters of it clean energy. Yet, the first five years remain dominated by fossil projects. This contradiction makes nuclear not a curiosity but a candidate for necessity. Across the world, more than 80 small modular reactor designs are advancing, with Russia and China already operating them. For an archipelago of 17,000 islands, modularity is a gift. Units of a few hundred megawatts (MW), built in factories and shipped like maritime cargo, can be installed gradually to match demand. The attraction is clear. New reactors promise electricity at or below the price of imported liquefied gas, modular units bring flexibility to a nation where power must cross seas, and mastering the atom signals that Indonesia is no longer only an exporter of commodities but a maker of technology. It is the portrait of a nation seeking to define itself not only by its geography but by the power of its ideas.

Grand visions are hollow without institutions. Indonesia needs a program office with a presidential mandate to coordinate utilities, regulators and ministries. A single line in the official power plan naming nuclear with a clear date – such as 500 MW of modular reactors by 2032 in Sumatra or Kalimantan – would transform aspiration into a calendar. Longer term, the government has set its sights on 10 GW of nuclear by 2040 and up to 40 GW by mid-century.

The legal framework must also catch up. The energy policy of 2014 still labels nuclear as a last resort. Liability rules remain modest compared with global norms. The nuclear statute itself was written before today's institutions even existed. Updating these rules would not only clear the way for investment; it would show citizens and investors that the state has the confidence to govern the atom responsibly. Indonesia's electricity market has one buyer: The state utility. Independent power producers succeed only if their contracts are bankable. For nuclear, they must be honest from the start. Waste and decommissioning cannot be afterthoughts. Reliability must be written in, with rewards for consistency and consequences for failure. Investors will watch whether procurement is transparent and predictable. Communities will watch whether projects bring jobs and local development. Both will watch whether oversight is strong enough to keep promises real. The lesson is simple: bad tenders kill good projects, but good contracts can turn ambition into steel and light.

Indonesia's choice unfolds against a backdrop of regional developments. The Philippines has reactivated its long-dormant plant, Vietnam is reevaluating and Singapore has signed cooperation pacts. Meanwhile, China and South Korea are racing ahead, bundling reactors with financing. In a world where supply chains are weapons, choosing a reactor is not only a technical act but a diplomatic one. Indonesia's geothermal reserves are vast, its floating solar potential immense. Yet, intermittency and land disputes slow progress. Coal still supplies more than half of the power, and even as the president pledges to phase it out within fifteen years, plans still include almost 27 GW of new coal in the coming decade. Without firm, clean capacity, both climate targets and growth ambitions are at risk. Nuclear is not a cure-all, but it may be the keystone that allows the arch to stand. Handled well, nuclear power could demonstrate that an emerging democracy can industrialize without carbon and without illusions. Mishandled, it could become another generation's deferred dream, a Muria project replayed in slow motion. This is about more than MW. It is about resilience and credibility in a century where energy defines

power more than oil ever did. For a nation of 280 million, endurance will be measured not only in export statistics but in kilowatt-hours that are clean, steady and decisively its own. Picture a fishing boat off Bangka Island, nets spread over waters once scarred by tin dredging. Behind it, a compact reactor hums quietly. Homes glow. Workshops run late. Children study under light that never falters.

That is not a fantasy; it is a wager, one that depends not on decisions 50 years from now, but in the next five. Indonesia's nuclear path is not only a domestic experiment; it is a parable for every emerging economy caught between coal dependency, renewable potential and geopolitical rivalry. If a sprawling democracy of 280 million can design rules, update laws and mobilize private capital for nuclear energy, others from Africa to Latin America may find a road map. If it stumbles, the world will take note of how even the most ambitious climate pledges can dissolve under the weight of political hesitation. This debate intensifies as a new administration settles into Jakarta. President Prabowo Subianto has promised rapid industrial growth under his Asta Cita vision while balancing fiscal realities and social expectations. His ministers speak of phasing out coal within 15 years even as state companies still plan nearly 27 GW of new coal plants. The House of Representatives debates revisions to the nuclear law, while regulators jockey for influence. These contradictions show why the nuclear wager is ultimately political. It is not just about MW but about whether a new government can translate ambition into durable institutions. What Indonesia decides in this decade will echo far beyond its grids. It is not merely an energy policy; it is a declaration of national confidence, the resolve to be a maker of destiny rather than a taker of circumstance. If managed wisely, the atom will not be a symbol of fear but the quiet script of a nation's ascent.

Russia plans to extend first private railway

Investors are considering plans to extend the Pacific Railway, Russia's first modern private railway, to serve the Tunguss coal basin in Siberia, according to Dmitry Demeshin, the governor of Khabarovsk Krai in the far east of the country.

The 531km Pacific Railway is being built by mining company Elga at a cost of Roubles 147bn ($US 1.76bn). It will connect the mine at Elga in the Sakha Republic, which with reserves of 2.1 billion tonnes of coking coal is one of the largest in the world, with an export terminal at Port Elga on the Sea of Okhotsk.

Construction was officially launched on September 4 with a ceremony attended online by the president of Russia, Vladimir Putin.

Forming the third main line to serve the far east of Russia, alongside the Trans-Siberian Railway and the Baikal - Amur main line, the Pacific Railway is expected to carry 30 million tonnes of freight next year, according to Elga. Until the end of this year, the railway will operate in trial mode.

In parallel, work continues on the railway's second branch, which is expected to increase capacity to 50 million tonnes a year. And as Demeshin told Russian state news outlet Interfax, plans are already in motion to extend the railway further westwards.

"In this way, we will connect the three largest Russian regions and the railway will run from the Krasnoyarsk Krai all the way to the Pacific Ocean," Demeshin says.

Although the new railway is designed for Elga export coal traffic, it is of strategic importance to the entire Russian economy, as it is expected to relieve both the Baikal - Amur main line and Trans-Siberian Railway.

Over the last three years, the eastern part of the Russian Railways (RZD) network has been struggling to cope with a sharp increase in freight traffic, reflecting the growing need for Russian producers to gain access to the markets of the Asia-Pacific region for goods previously exported to western markets.

Uniper sells German coal power plant

Uniper SE has signed an agreement to divest the Datteln IV coal-run power plant in North Rhine-Westphalia to ResInvest Group AS.

The plant is among assets it has agreed to sell to satisfy fair-competition guardrails imposed by the European Commission in approving Uniper's bailout by the German government in late 2022.

Commissioned 2020, the Datteln plant has a net output of 1,052 megawatts (MW). It supplies electricity and district heating to households, as well as traction power to rail operator Deutsche Bahn, according to German power and gas utility Uniper.

The over 100 employees at the site will transfer to Czechia's ResInvest, Uniper said in a statement on its website.

The parties agreed not to disclose the purchase price, Uniper said.

The transaction is subject to regulatory approvals, it said.

"By acquiring Datteln 4, we are pursuing our strategy of investing in infrastructure assets where we see long-term value. We are committed to ensuring reliable operations today, while remaining ready to meet future energy needs", commented ResInvest founder and chair Tomas Novotny.

Under Germany's Coal Phase-Out Act, the country is to close down its last coal-fired power facility by 2028.

"The sale of this non-strategic investment is part of the conditions that Uniper must fulfill under EU state aid law", Uniper said. "On 20 December 2022, the EU Commission approved the stabilization package for Uniper under EU state aid law".

Last month Uniper said it had signed an agreement selling its district heating network serving over 14,000 customers in the Ruhr region to Steag Iqony Group's Iqony Fernwaerme GmbH.

In July Uniper said it had sold its 18.26% stake in AS Latvijas Gaze, which is involved in natural gas trading and sales in the Baltics, to co-venturer Energy Investments SIA.

Latvijas Gaze sells gas in Estonia, Finland, Latvia and Lithuania. In Latvia's household sector, it is the biggest gas supplier, Latvijas Gaze says on its website.

In February Uniper completed the sale of its North American power portfolio. The sale covered "power purchase and sale contracts and energy management agreements in the North American power markets ERCOT (North, South, West and Houston), WEST (WECC and CAISO) and CENTRAL (MISO and SPP) through a number of transactions with several counterparties", Uniper said then.

The North American dispositions excluded Uniper's gas portfolio and hydrogen-related activities.

In January Uniper completed the sale of its natural gas-fired power plant in Gonyu, Hungary, to the local subsidiary of France's Veolia SA. Commissioned 2011, the power plant generates up to 430 MW, according to Uniper.

In the other divestments completed as part of the bailout conditions, Uniper in May 2023 sold its marine fuel trading business in the United Arab Emirates and its 20% indirect stake in the BBL gas pipeline linking the Netherlands and the United Kingdom.

The other assets in the divestment package, which must be completed 2026, consist of an 84% stake in Unipro in Russia, a 20% stake in the OPAL pipeline and Uniper's international helium business, Uniper says on its website.

Kazakhstan putting hydrocarbons and modern coal tech at forefront of its energy game plan

Hydrocarbons will continue to play a key role in the global energy sector and, consequently, in Kazakhstan's energy sector, said President of Kazakhstan Kassym-Jomart Tokayev at a solemn ceremony at Akorda, congratulating the country's oil and gas industry workers, Trend reports.

The president thinks that the global oil and gas industry is the apple of many countries' eyes and a hot topic among renowned experts. The future of the industry is being discussed in terms of its impact on the prospects for global economic development.

"From my perspective, hydrocarbons are poised to maintain a pivotal position in the global energy landscape and, by extension, within Kazakhstan's energy framework. Insights derived from a plethora of international contexts, particularly within the European landscape, indicate that alternative energy modalities can fulfill a supplementary role.

Moreover, it is imperative to focus on the deployment of cutting-edge technologies designed for the comprehensive refinement of natural coal for its industrial applications, particularly in the infrastructure of energy generation facilities.

It is widely recognised that coal constitutes approximately 70% of Kazakhstan's energy portfolio; our nation ranks among the top ten global coal producers, and this strategic asset should not be relinquished but rather leveraged optimally," said Tokayev.


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