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NET ZERO EMISSIONS IN MINING: AN OVERVIEW

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ABSTRACT

The mining sector is energy-intensive, with significant emissions resulting from the use of fossil fuels for electricity, heat, and transport. Energy consumption is a major contributor to both Scope 1 and Scope 2 emissions. Coal mining is a major source of methane emissions, which has a higher global warming potential than CO_2. Methane is released during the extraction and processing of coal. Emissions from the transportation and processing of mined products contribute significantly to the overall carbon footprint. Key decarbonization strategies include the integration of renewable energy sources, electrification of mining equipment and the development of carbon capture and storage (CCS) technologies. In spite of these initiatives, the industry encounters several obstacles, including high costs, technical limitations and inconsistent regulatory frameworks. This paper details out the challenges and barriers and the strategies for net zero emissions adopted by different mining companies through case studies. This paper is an attempt to assess the emerging technologies and innovations and examine the policy framework and regulations to achieve net zero goal.

KEY WORDS : Net zero emissions, Mining, Carbon capture and storage, Greenhouse gas, CO_2 emissions, Green technologies

INTRODUCTION

The mining industry is a significant contributor to global greenhouse gas (GHG) emissions, primarily due to its energy-intensive operations. Achieving net zero emissions in mining involves reducing these emissions to as close to zero as possible, with any remaining emissions being offset by equivalent carbon removal efforts. The global emissions of carbon dioxide equivalent (CO_2) from nickel mining in 2019 were over 120 million metric tons. The mining of copper in 2019 resulted in emissions of around 109 million metric tons of CO_2. In 2019, the mining of iron ore (seaborne) was responsible for roughly 96 million metric tons of CO emissions (Fig. 1). About 89 million metric tons of CO_2 were released in 2019 as a result of metallurgical coal mining (seaborne). In 2019, the mining of gold was responsible for approximately 81 million metric tons of CO_2 emissions (Azadi *et al*., 2020; Cox *et al*., 2022).

Because of excessive dependence on fossil fuels for power, heating, and transportation, the mining industry is a significant cause of air pollution. One of the main causes of emissions in both Scope 1 and Scope 2 is energy usage. Methane emissions, which coal mining produces in large quantities, are more likely to contribute to climate change than carbon dioxide emissions. The coal extraction and processing discharge methane into the atmosphere. A large portion of the total carbon footprint is attributable to emissions caused by the mining process, including transportation and processing. This encompasses emissions produced by downstream processing facilities, as well as those

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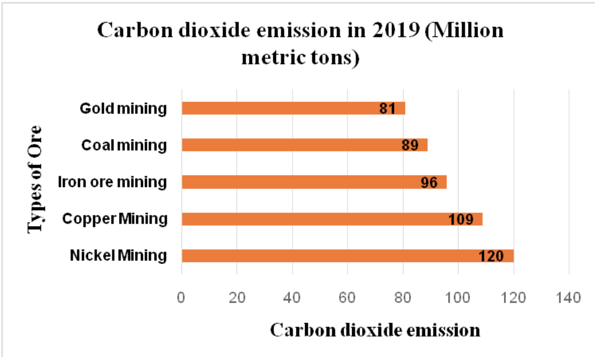

Fig. 1. CO_2 emissions in 2019

from shipping and rail transport (Legge *et al.*, 2021).

The mining company's direct ownership or control of a source constitutes Scope 1 emissions. The majority of these pollutants are caused by the burning of fossil fuels in mining machinery and cars. The use of diesel-powered machinery, including loaders, excavators and haul trucks, is essential in the mining industry. Carbon dioxide (CO_2) and other greenhouse gases are produced in large quantities when these devices use diesel fuel. One source of greenhouse gas emissions is the use of explosives in the mining industry. Surface and underground miners alike frequently use blasting rocks and get to the ore below. Diesel or natural gas generators are used by some mining companies to provide their own electricity. Direct emissions are produced when these fuels are used (Reþitoðlu *et al.,* 2015).

Scope 2 emissions are those that are generated indirectly as a result of the mining operation's use of purchased power, steam, heat, or cooling. Ore processing, ventilation, and lighting are just a few of the many electrical tasks that mining companies do. Scope 2 emissions are produced if the power comes from fossil fuels like coal or natural gas. There is a significant regional variation in the carbon intensity of the power grid. Scope 2 emissions from mining activities are likely to be greater in regions where fossil fuels are used extensively by the grid (Arnold and Toledano, 2021; Fankhauser *et al.*, 2022).

All the way from the extraction of fuels and transportation to the final processing and distribution of the extracted minerals-all of these activities contribute to what are known as Scope 3 Emissions, which are indirect emissions. It is not uncommon for mining companies to produce more than 95% of their carbon footprint through Scope 3 emissions. The mining process itself produces these pollutants, as does the extraction and transportation of the fuels and raw materials utilized in the process. Upstream emissions are produced, for instance, during the processes of diesel fuel extraction and refining. These emissions are produced when materials from mines are processed, transported and used. Metal refining and smelting, for instance, is a major source of air pollution. Another source of downstream emissions is the conveyance of extracted minerals to consumers. Scope 3 emissions also include byproducts of using mined materials, such as metals in manufacturing or coal burned in power stations (Arnold *et al.*, 2021; Fankhauser *et al.*, 2022).

A number of reasons are propelling the mining industry toward zero emissions: the necessity to combat climate change, stakeholder expectations and legal mandates. To get there, mining companies are doing things like using renewable energy, making all of their mining equipment electric and putting carbon capture and storage (CCS) systems in place. Significant obstacles, such as expensive expenses, technological constraints and varied regulatory frameworks, persist despite these endeavours.

METHODOLOGY

The methodology for this study involves a comprehensive review of existing literature, case studies, and industry reports on net zero emissions in mining. The following steps outline the approach taken:

➢ Literature Review

A thorough review of academic papers, industry reports, and government publications was conducted to gather information on current strategies, challenges and barriers related to net zero emissions in mining. Academic publications, the World Bank, and the International Council on Mining and Metals (ICMM) are among the important sources.

➢ Case Studies

Detailed case studies of mining companies that have made significant progress towards achieving net zero emissions were analysed. These case studies provide insights into the specific strategies and technologies being implemented, as well as the challenges and successes encountered. Companies such as Fortescue, Rio Tinto, and Vale were included in the analysis.

- **Technology Assessment**

An assessment of emerging technologies and innovations in the mining sector was conducted to evaluate their potential to contribute to net zero emissions. This included technologies such as electric mining equipment, hydrogen fuel cells and advanced CCS systems.

- **Policy and Regulatory Analysis**

The study examined existing policy frameworks and regulatory mechanisms that support the transition to net zero emissions in mining. This analysis included a review of carbon pricing mechanisms, subsidies for green technologies and International agreements.

Challenges and Barriers

In the mining industry, reaching net-zero emissions is an intricate and multi-faceted task. Key obstacles and difficulties include as given in Table 1.

Table 1. Key obstacles and difficulties (Jones, 2023; Quaralia *et al*., 2023).

Key Difficulties	Descriptions
High Energy Consumption	It takes a lot of power and fuel for mining operations to get the job done. Mineral processing, transportation, and extraction all need a lot of energy. Because many mining operations are large and situated in distant areas, switching to renewable energy sources is a huge obstacle.
Fugitive Emissions	Fugitive methane emissions are from coal mining account for a significant number of mining-related emissions. The difficulty in capturing and controlling these pollutants is a substantial obstacle to reaching net-zero emissions.
Ore Grade Decline	Energy consumption rises in relation to the amount of precious minerals extracted and processed when ore grades decline. This makes it more difficult to reduce emissions and raises the carbon footprint of mining activities.
Technological Limitations	Some emission-reduction technologies are still in their infancy, but they show promise; for example, electrifying mining equipment and using hydrogen fuel cells. Important obstacles include the high prices and technical difficulties of these technologies.
Infrastructure and Logistics	Mining operations are already complicated enough without having to worry about the necessary infrastructure, such as transportation and electricity supply. Renewable energy sources and well-developed transportation networks are sometimes inaccessible to mining sites because of their remote locations.
Regulatory and Policy Challenges	The mining regulatory landscape is intricate and differs greatly between locations. Best practices and technology for lowering emissions may be impeded by inconsistent legislation and policy.
Economic Pressures	Economic incentives to maximize production while minimizing expenses drive the mining industry. Companies face the challenge of prioritizing investments in new technology and practices that reduce emissions, as these investments can be costly and may not deliver immediate financial rewards.
Supply Chain Emissions	The mining industry's total carbon footprint is increased by emissions that occur along the supply chain, which includes the manufacturing and transportation of mining equipment and supplies. The entire supply chain must work together to address these pollutants.
Social and Environmental Impacts	Communities may be uprooted and ecosystems devastated as a result of mining operations, which can have far-reaching social and environmental consequences. Striking a balance between mineral resource extraction and environmental and community protection is no easy feat.
Demand for Critical Minerals	Massive amounts of essential minerals are needed for the shift to renewable energy systems and electric automobiles, two examples of clean energy technology. Reducing emissions from mining operations while meeting this demand is no easy feat. In spite of these obstacles, the mining industry can nonetheless play a role in bringing about a low-carbon economic transformation. The mining industry can help the world reach its goal of net-zero emissions by cutting back on carbon emissions, increasing operational efficiency and investing in renewable energy.

Case Examples

Leading mining firms' efforts and obstacles towards net zero emissions are highlighted in these case studies as discussed in Table 2. Each organization is taking action in its own special way to lessen its impact on the environment to ensure more sustainable future.

Technological Assessment

New technology and ideas are changing the mining industry in a big way, with the aim of cutting emissions and getting to zero emissions. Table 3 details a number of significant technological advancements that are currently having an impact.

Policy and Regulatory Analysis

To help the mining industry reach net-zero emissions, below are several important policy frameworks and regulatory mechanisms:

Paris Agreement

A worldwide framework, with additional efforts to limit the increase to 1.5 degrees Celsius, the Paris

Table 2. Efforts and obstacles towards net zero emissions (Issa *et al*., 2023; Kumar *et al*., 2023).

Overview	Strategies	Challenges	Outcomes
Fortescue Metals Group, an Australian iron ore company, has set ambitious targets to achieve net zero operational emissions by 2030 and net zero Scope 3 emissions by 2040. .	Fortescue is putting a lot of money into solar and wind farms and other renewable energy projects so that it can power its mining operations. As a sustainable alternative to diesel, the company is working on green hydrogen projects to power its mining vehicles and equipment. To lessen its impact on the environment, Fortescue is switching to electric power for its mining trucks and equipment.	The initial investment in renewable energy and electrification technologies is significant. Developing and scaling green hydrogen techno-logy presents technical challenges.	With its current rate of carbon footprint reduction, Fortescue is well on its way to achieving its net zero goals.
Rio Tinto, one of the world's largest mining companies, aims to achieve net zero emissions by 2050.	In order to decrease Scope 2 emissions, Rio Tinto is boosting its usage of renewable energy sources like hydroelectric power. In order to collect and store CO2 emissions, the business is investing in CCS technologies. In an effort to lower total energy use, Rio Tinto is executing energy saving measures at all of its mining locations.	Inconsistent regulatory frameworks across different regions pose challenges for Implementing uniform strategies. The development and deployment of CCS technologies are still in the early stages.	Rio Tinto has achieved significant reductions in its emissions and continues to invest in innovative technologies to reach its net zero goals.
Vale, a Brazilian mining company, is committed to achieving net zero Scope 1 and 2 emissions by 2050.	Vale has transitioned to 100% renewable energy for its operations in Brazil. The company is electrifying its mining equipment and vehicles to reduce emissions from diesel. Vale is adopting sustainable mining practices, such as reforestation and biodiversity, conservation, to offset its carbon footprint.	The cost of transitioning to renewable energy and electrification can be a financial burden. Implementing new technologies and practices requires overcoming technical barriers.	Vale is well on its way to achieving its net zero emissions goals, having made considerable strides in this direction.

Table 2. *Continued ...*

Overview	Strategies	Challenges	Outcomes
Hindustan Zinc Limited, a leading zinc producer in India, has committed to achieving net zero emissions by 2050	In an effort to lessen its dependency on fossil fuels, HZL is putting money into renewable energy initiatives. As a whole, the business is reducing its energy use by executing energy saving measures. In order to compensate for its remaining emissions, HZL is looking into carbon offsetting initiatives including afforestation and reforestation.	Renewable energy and efficiency measures require a large financial outlay at the outset. Technical hurdles exist in the development and expansion of carbon offsetting projects.	HZL has made substantial progress in reducing its carbon footprint and is on track to meet its net zero targets.
Tata Steel, one of India's largest steel producers, aims to achieve net zero emissions by 2050.	In an effort to lessen its impact on the environment, Tata Steel is ramping up its usage of renewable energy sources like wind and solar electricity. In order to collect and store CO2 emissions, the business is investing in CCS technologies. Reforestation and biodiversity conservation are two examples of Tata Steel's sustainable mining techniques that it is using to reduce its environmental impact.	Problems with executing uniform tactics arise from inconsistent regulatory frameworks throughout various areas. We are still in the early phases of developing and deploying CCS technologies.	Tata Steel has invested in new technology to accomplish its zero-emissions targets, and the company has reduced its emissions significantly.
The biggest coal producer in India, Coal India Limited, has pledged to reduce its carbon emissions and reach zero emissions by the year 2070.	In an effort to lessen its need on coal, CIL is funding alternative energy initiatives, such as solar power. In an effort to lower overall energy use, the company is executing energy saving measures across all of its mining operations. CIL is looking into afforestation and replanting as carbon offsetting projects to make up for its leftover emissions.	A financial burden may arise from the expense of switching to renewable energy sources and energy efficiency technologies. It is necessary to overcome technological obstacles in order to implement new techniques and technology.	CIL's emissions reduction efforts are well underway, and the company is on pace to achieve its net zero goals.

Agreement aims to keep the rise in global warming well below 2 degrees Celsius over pre-industrial levels. In order to lower their emissions of greenhouse gases, countries must establish and meet nationally determined contributions (NDCs). The mining sector is influenced by these national pledges that promote the use of low-carbon practices and technology (Jones, 2023).

International Council on Mining and Metals (ICMM)

By 2050 or earlier, the ICMM has pledged that its members will have eliminated emissions of all greenhouse gases, including those in Scopes 1 and 2. There are around 650 locations in over 50 countries. To help the mining industry become more sustainable and reduce emissions, the ICMM has put out some rules of thumb.

Table 3. Adoption of emerging technologies and innovations achieving net-zero goals (Tang *et al.*, 2023; Onifade *et al.*, 2024).

Key technologies	Innovations	Descriptions
Automation and Electrification	Autonomous Vehicles	The use of autonomous trucks and drills reduces fuel consumption and increases efficiency. These vehicles can operate continuously without breaks, leading to lower emissions.
	Electric Vehicles	Replacing diesel-powered machinery with electric alternatives significantly reduces greenhouse gas emissions. EVs are particularly beneficial in underground mining, where they reduce ventilation requirements due to lower heat and particulate emissions.
Renewable Energy Integration	Solar and Wind Power	Many mining operations are integrating renewable energy sources to power their activities. Renewable energy sources, such as solar panels and wind turbines, lessen the need for fossil fuels.
	Hybrid Energy Systems	Combining renewable energy with battery storage and traditional power sources ensures a stable and reliable energy supply, even in remote locations.
Advanced Data Analytics and AI	Predictive Maintenance	Predicting when equipment may go down using AI and ML can cut down on downtime and boost productivity. Reduced emissions and energy usage result from this.
.	Optimization Algorithms	Advanced algorithms optimize mining processes, from exploration to extraction, reducing waste and energy use.
Carbon Capture and Storage (CCS)	Carbon Sequestration	Technologies that capture and store carbon dioxide emissions from mining operations are being developed and implemented. This helps in reducing the overall carbon footprint of the industry.
In-Situ Mining	In-Situ Recovery (ISR)	This method involves extracting minerals without traditional mining techniques. Instead, In order to dissolve the minerals in the ore body, a solution is injected into it and subsequently pumped to the surface. ISR reduces surface disturbance and emissions.
Digital Twins and Simulation	Digital Twins	Creating digital replicas of mining operations allows for real-time monitoring and optimization. This technology helps in identifying inefficiencies and reducing energy consumption.
	Simulation Tools	Advanced simulation tools model mining processes to find the most efficient and sustainable methods.
Hyperspectral Imaging and LiDAR	Hyperspectral Imaging	This technology provides detailed information about mineral composition and distribution, improving exploration efficiency and reducing unnecessary drilling.
	LiDAR (Light Detection and Ranging)	LiDAR technology is used for precise mapping and monitoring of mining sites, enhancing safety and reducing environmental impacts.
Water Management Technologies	Water Recycling	Advanced water treatment and recycling technologies reduce water consumption and minimize the environmental impact of mining operations.
	Desalination	In areas with limited freshwater resources, desalination technologies provide a sustainable water supply for mining activities.

Task Force on Climate-related Financial Disclosures (TCFD)

The TCFD suggests ways in which businesses might be transparent about the financial risks and possibilities posed by climate change. Investors and stakeholders can gain a better understanding of how climate change is affecting firms, especially those in the mining sector, through these disclosures. Mining businesses are encouraged to implement measures for lowering emissions and managing climate risks by the TCFD framework.

Carbon Pricing Mechanisms

Companies are encouraged to decrease their emissions through carbon pricing schemes, which include cap-and-trade systems and carbon taxes. Mining businesses are incentivized to invest in low-carbon technologies and practices through these methods, in order to minimize their carbon footprint (Bataille, 2020).

National and Regional Regulations

To aid in the shift to zero emissions, several nations have enacted laws and policies. For instance, by 2050, the goal of the EU's Green Deal is to have Europe achieve carbon neutrality. Emissions reduction, renewable energy, and energy efficiency laws all have an effect on the mining industry (Bataille *et al*., 2021).

Sustainable Finance Initiatives

Businesses can receive financial incentives to invest in green projects through sustainability-linked loans and green bonds, two examples of sustainable finance efforts. Renewable energy projects, energy efficiency upgrades, and other low-carbon technology are subsidized by these programs to help the mining industry reach net-zero emissions.

Industry Collaboration and Partnerships

The only way to get zero emissions is for mining firms, governments, and other interested parties to work together. Climate Smart Mining (CSM) is an effort by the World Bank to encourage environmentally responsible mining methods and fund research into low-carbon technology.

DISCUSSION

There is a dearth of research that covers the whole spectrum of mining operations' lifecycle emissions, from extraction to disposal. To fully comprehend the environmental impacts and find ways to reduce emissions at every stage of the lifecycle, additional study is required. Communities and workers in the mining industry will face substantial social and economic challenges as a result of the shift to zero emissions. To guarantee a fair transition with minimal negative effects and maximum positive outcomes for all parties involved, more research is required to formulate appropriate measures. Achieving net-zero emissions requires precise data collecting and monitoring. In order to collect data on emissions and energy consumption in mining operations in real-time, more research into improved monitoring technology and procedures is required.

In an effort to lessen their impact on the environment, mining corporations are putting more money into renewable energy. This includes solar, wind, and hydroelectric electricity. One typical method is to generate renewable energy on-site, while another is to enter into a power purchase agreement (PPA). One important step towards lowering Scope 1 emissions is switching mining equipment from diesel to electric power. Research into trolley-assist systems, fully electric vehicles and hybrids is ongoing. To store CO_2 emissions from mining operations underground, CCS technologies are being developed. Emissions reduction in processing facilities is an area where this strategy works better.

Implications

The mining industry has the potential to significantly improve environmental conditions by reducing pollution of air and water, preserving natural resources, and reaching a net-zero emissions level. On a worldwide scale, this will aid in the battle against climate change and for sustainable development. New business opportunities may emerge in areas such as sustainable mining practices, green technology, and renewable energy if the mining industry were to transition to zero emissions. More employment opportunities, faster economic growth, and enhanced global competitiveness could result from this. As mining firms strive for zero emissions, there will be significant social consequences for mining towns and their personnel. Prioritizing affected communities and workers during the transition is of the utmost importance. Proactively implementing net zero plans is essential for mining businesses to remain compliant with constantly evolving rules and evade fines. Investment, reputation, and stakeholder relations can all benefit from this.

CONCLUSION

Leading mining firms' efforts and obstacles towards net zero emissions are highlighted in these case studies. A more sustainable future is within reach and each organization is taking action in its own special way to lessen its impact on the environment. The mining sector may achieve net zero emissions and contribute to a more sustainable future by addressing these difficulties through concerted efforts from academia, government and industry. For mining to achieve net-zero emissions, strong regulatory structures and policies are required. Policies that encourage the use of environmentally friendly technology and punish those that produce a lot of harmful emissions should be the primary goal of future initiatives.

Electric mining equipment, hydrogen fuel cells, and carbon capture and storage (CCS) are examples of the cutting-edge technology that will be necessary to achieve net-zero emissions in the mining industry. Research and development (R&D) spending should be sustained in order to overcome technological barriers and hasten the commercialization of these inventions. Renewable energy sources, such as solar, wind, and hydroelectric power, can be used to reduce emissions from mining operations. Future research should focus on developing efficient energy storage technologies and determining the most efficient means of integrating these energy sources into the existing mining infrastructure.

Conflict of Interest- None

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