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Research Article

Battery Electric Mining Equipment for Green and Sustainable Mining

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Abstract

The mining industry is undergoing a major transformation toward sustainable and environmentally responsible operations. Conventional diesel-powered mining equipment contributes significantly to greenhouse gas emissions, ventilation costs, noise pollution, and occupational health hazards. Battery Electric Mining Equipment (BEME) has emerged as a promising alternative that supports mine decarbonization and improves operational efficiency. The findings indicate that battery electric equipment significantly reduces carbon emissions, ventilation requirements, and maintenance costs while providing improved working conditions. Although the initial capital investment is higher, long-term operational savings and environmental benefits make battery electric technology a viable solution for sustainable mining. The study concludes that widespread adoption of battery electric equipment can contribute substantially to green mining initiatives and support global climate goals.

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1. INTRODUCTION

1.1 Background

Mining remains a foundational industry that supplies raw materials essential for global infrastructure, energy production, and industrial manufacturing. Traditionally, mining operations have relied heavily on diesel-powered heavy machinery—including haul trucks, Load-Haul-Dump (LHD) loaders, and drilling rigs—to handle material extraction and transport. While robust, diesel internal combustion engines consume substantial amounts of fossil fuels and emit significant volumes of greenhouse gases (GHGs), diesel particulate matter (DPM), and excess heat. In underground mining environments, these emissions severely degrade ambient air quality, necessitating high-capacity ventilation and cooling infrastructure to maintain safe working conditions (Hooli & Halim, 2025). Growing global concerns regarding climate change and environmental sustainability have driven the mining sector toward cleaner technological paradigms. Battery electric mining equipment has emerged as a practical, high-efficiency solution that replaces conventional internal combustion engines with electric drivetrains, thereby addressing both environmental and occupational challenges.

1.2 Need for the Study

The mining industry is experiencing a paradigm shift toward mine electrification due to increasing environmental concerns, stringent regulatory frameworks, technological advancements, and the growing emphasis on sustainable resource extraction. Conventional diesel-powered mining equipment contributes significantly to greenhouse gas emissions, air pollution, fuel consumption, and operating costs, making it increasingly challenging for mining companies to meet evolving environmental standards and sustainability objectives. The implementation of stricter environmental regulations at national and international levels has accelerated the adoption of cleaner and more energy-efficient mining technologies aimed at reducing carbon emissions and improving overall environmental performance (Rishi, 2025).

In addition to regulatory pressures, the volatility of diesel fuel prices has substantially increased the operational costs associated with conventional mining fleets, encouraging mining companies to explore economically viable alternatives. Simultaneously, the mining sector is committed to achieving net-zero carbon emissions and fulfilling Environmental, Social, and Governance (ESG) objectives, which require significant reductions in Scope 1 and Scope 2 emissions through the electrification of mining operations. Worker health and safety also remain a critical concern, particularly in underground mines where diesel-powered equipment generates toxic exhaust gases, diesel particulate matter, and excessive heat, adversely affecting workplace conditions and increasing ventilation requirements. Battery electric mining equipment offers a practical solution by eliminating tailpipe emissions, improving underground air quality, reducing ventilation demand, and enhancing occupational safety.

Furthermore, increasing expectations from governments, investors, and stakeholders for environmentally responsible mining practices have accelerated the transition toward sustainable and low-carbon mining technologies. Battery electric equipment not only supports environmental conservation but also improves operational efficiency, reduces maintenance requirements, and contributes to the long-term economic sustainability of mining operations. Therefore, a comprehensive evaluation of the operational, environmental, and economic impacts of battery electric mining equipment is essential to facilitate informed decision-making and support the mining industry's transition toward cleaner, safer, and more sustainable mining practices.

1.3 OBJECTIVES

This study aims to systematically investigate the operational, environmental, and economic implications of adopting battery electric mining equipment in both underground and surface mining operations. The research examines the current status and applications of battery electric machinery across different mining environments and compares its performance with conventional diesel-powered equipment in terms of productivity, operational efficiency, maintenance requirements, and reliability. Particular emphasis is placed on evaluating the environmental benefits of mine fleet electrification, including reductions in greenhouse gas emissions, improvements in underground air quality, decreased ventilation demand, and enhanced energy efficiency, all of which contribute to the objectives of sustainable mining (Singh, 2026). Furthermore, the study assesses the economic feasibility of battery electric mining fleets through a comprehensive Total Cost of Ownership (TCO) analysis that considers capital investment, operating costs, maintenance expenses, and lifecycle costs. Finally, the research evaluates the strategic role of battery electric mining equipment in advancing sustainable mining by integrating environmental, operational, and financial perspectives to provide insights for industry practitioners, policymakers, and researchers in the transition toward low-carbon and intelligent mining systems.

1.4 Scope of the Study

This study focuses primarily on battery electric LHD loaders, heavy haul trucks, and drilling rigs utilized in underground and surface mining environments. The analysis examines technical performance parameters, environmental metrics, economic trade-offs, and infrastructure requirements using secondary empirical data, technical publications, and industry case studies.

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2. LITERATURE REVIEW

2.1 Overview of Mine Electrification

Recent academic literature identifies mine electrification as a cornerstone strategy for decarbonizing the extractives industry and achieving broader sustainable development goals (Hooli & Halim, 2025). Traditional internal combustion engines operate at relatively low thermal efficiencies (typically 30–35%), losing a majority of consumed energy as waste heat and exhaust. In contrast, electric drivetrains achieve energy conversion efficiencies exceeding 85–90%, while eliminating direct tailpipe emissions entirely (Hooli & Halim, 2025).

2.2 Battery Technologies in Mining

Selecting appropriate battery chemistries is crucial for meeting the intense duty cycles of heavy mining operations. The primary lithium-ion chemistries utilized in heavy mining equipment include:

- **Lithium Iron Phosphate (LFP):** Widely favored for its exceptional thermal stability, long cycle life, and high safety margin in hazardous underground environments.
- **Nickel Manganese Cobalt (NMC):** Preferred in applications requiring higher specific energy density to maximize operational range between charges, though requiring stringent thermal management.

Studies emphasize that modern lithium-ion chemistries support fast-charging protocols and regenerative braking, which captures gravitational potential energy during downhill loaded haulage to recharge the battery system (Hooli & Halim, 2025).

2.3 Battery Electric Loaders

Load-Haul-Dump (LHD) vehicles represent one of the most energy-intensive equipment classes in underground mining. Empirical evaluations confirm that transitioning from diesel to battery electric LHDs dramatically reduces localized heat generation and exhaust pollutants. Consequently, mines report substantial reductions in required auxiliary ventilation volume and associated power draw (Hooli & Halim, 2025).

2.4 Battery Electric Haul Trucks

Field evaluations of battery electric haul trucks demonstrate substantial reductions in lifecycle energy consumption compared to diesel fleets. Electric haul trucks deliver superior torque and ramp-climbing speeds while eliminating direct diesel combustion, leading to marked decreases in overall site greenhouse gas emissions.

2.5 Environmental Benefits

Synthesizing recent findings reveals several key environmental advantages of my electrification:

- **Direct Emission Elimination:** Complete removal of Scope 1 carbon dioxide (CO_2), nitrogen oxides (NO_x), and carbon monoxide (CO) emissions at the point of operation.
- **Particulate Matter Suppression:** Elimination of hazardous diesel particulate matter (DPM), significantly improving underground working conditions.
- **Acoustic Mitigation:** Substantial reduction in operational noise levels, protecting operators and surrounding personnel from acoustic fatigue and hearing hazards.
- **Thermal Burden Reduction:** Lower heat output from electric motors reduces subterranean air-cooling requirements (Hooli & Halim, 2025).

2.6 RESEARCH GAP

While existing literature extensively documents the localized environmental and health benefits of battery electric vehicles (BEVs), comprehensive syntheses incorporating long-term total cost of ownership, real-world battery degradation under heavy duty cycles, and charging infrastructure optimization remain limited. This study addresses this gap by synthesizing environmental, operational, and financial parameters into an integrated comparative framework.

3. METHODOLOGY

3.1 Research Design

This study utilizes a qualitative and quantitative comparative research design based on secondary data analysis. Performance metrics of conventional diesel-powered equipment are benchmarked directly against equivalent battery electric models operating under comparable duty cycles.

3.2 Data Collection

Data were compiled from peer-reviewed scientific journals, corporate sustainability reports from major mining enterprises, technical equipment documentation from OEMs (Original Equipment Manufacturers), and published industry white papers.

3.3 Parameters Considered

The evaluation evaluates three primary operational domains:

- **Environmental Parameters:** CO2 equivalent emissions, localized pollutant concentration (DPM, NOx), and ambient noise levels (dB).
- **Economic Parameters:** Capital expenditure (CapEx), diesel fuel costs, electricity tariffs, maintenance/overhaul expenses, and underground ventilation power costs.
- **Operational Parameters:** Equipment availability, continuous duty cycle runtime, battery charging/swapping times, payload capacity, and ramp speed efficiency.

3.4 Comparative Framework

A comparative analysis framework was established to systematically evaluate diesel and electric machinery across identical operational parameters to determine overall viability and economic payoff periods.

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4. STUDY AND ANALYSIS

4.1 Battery Electric Mining Equipment

Battery Electric Loaders

Underground battery electric loaders perform vital ore loading and short-distance transport operations. By replacing diesel engines with high-torque electric motors, these units deliver instantaneous torque, smoother acceleration, and zero tailpipe emissions. The absence of exhaust gases reduces required underground airflow velocity, generating direct savings on main fan power consumption.

Battery Electric Haul Trucks

Deployed in both underground declines and surface pits, battery electric haul trucks transport heavy tonnage over steep grade profiles. Their high mechanical efficiency and regenerative braking capabilities allow them to recover energy during descent, effectively recharging the battery and lowering net energy consumption per ton hauled.

Battery Electric Drills

Production and development drill rigs operate primarily in fixed underground faces. Electric-hydraulic and pure battery electric drills drastically diminish noise and vibration levels at the working face, improving operator safety, comfort, and communication while reducing site ventilation overhead.

4.2 Comparison Between Diesel and Battery Electric Equipment

Performance Parameter	Conventional Diesel Equipment	Battery Electric Equipment (BEV)
Direct Carbon Emissions	High (CO2 output)	Zero tailpipe emissions
Fuel / Energy Cost	High and volatile (Diesel fuel)	Significantly lower per kWh equivalent
Ventilation Demand	High (Requires high CFM to dilute exhaust)	Low (Only requires basic air refresh)
Maintenance Expenditure	High (Engine overhauls, oil, filters)	Moderate (Fewer mechanical wear parts)
Noise & Heat Output	High ambient noise and heat	Low noise and minimal heat generation
Upfront Capital Investment	Lower initial purchase cost	Higher initial CapEx (Battery pack costs)
Net Operating Cost (OpEx)	Higher lifetime operational cost	Lower lifetime operational cost

4.3 Environmental Analysis

Reduction in Greenhouse Gas Emissions

Because conventional diesel engines emit approximately 2.68 kg of $\text {CO}_2$ per liter of fuel burned, transitioning a fleet of heavy haulage equipment to battery power eliminates substantial direct greenhouse gas output. When paired with renewable grid power or on-site solar generation, full life-cycle emissions approach net zero.

Improved Subterranean Air Quality

In underground mines, diesel exhaust concentration poses acute health risks. Battery electric machinery eliminates diesel particulate matter (DPM) and toxic gaseous pollutants (NOx, CO), establishing safer and cleaner working environments that align with international occupational exposure standards.

Acoustic and Thermal Load Reduction

Electric drives operate at substantially lower decibel levels compared to internal combustion engines. Furthermore, because electric motors convert energy far more efficiently than diesel engines, they emit significantly less waste heat, lowering heat stress on underground workers and reducing air conditioning loads (Hooli & Halim, 2025).

4.4 Economic Analysis

Energy and Fuel Cost Savings

Electricity costs per unit of work completed are consistently lower than equivalent diesel fuel expenses. The superior energy efficiency of electric motors—combined with regenerative energy capture—yields net energy cost reductions of up to 50–65% per operational hour depending on local utility tariffs.

Ventilation Cost Savings

Ventilation fans represent one of the single largest electrical power consumers in underground mining, often accounting for 25–40% of total site energy demand. Because battery electric machinery produces zero combustion gases, mine airflow requirements can be reduced significantly, generating major long-term reductions in fan operating expenditures.

Maintenance Savings

Internal combustion engines require frequent oil changes, filter replacements, fluid checks, and costly periodic overhauls. Electric drivetrains contain significantly fewer moving parts, resulting in estimated maintenance cost reductions of 30–40% over the machine's operating lifespan.

4.5 Challenges in Implementation

High Initial Capital Cost

The primary barrier to widespread adoption is the high initial purchase price of battery electric equipment, which typically carries a 20–30% premium over diesel equivalents due to specialized battery chemistry and power electronics.

Charging Infrastructure Development

Deploying electric fleets requires heavy investment in electrical grid upgrades, underground fast-charging stations, or automated battery-swapping infrastructure to ensure continuous machine utilization.

Battery Lifespan and Replacement

Battery cell degradation under harsh mining duty cycles necessitates planned mid-life battery replacement, representing

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a major recurring capital expenditure that must be factored into life-cycle cost models.

4.6 Case Studies

Case Study 1: Underground Metal Mine Fleet Replacement

A deep underground metal mine replaced its conventional diesel LHD fleet with battery electric units. Operational tracking revealed a 100% elimination of localized diesel exhaust, enabling a 35% reduction in total ventilation fan energy consumption alongside marked improvements in underground air quality indices.

Case Study 2: Battery Electric Haulage Implementation

An operational trial evaluating heavy battery electric haul trucks on steep incline haulage demonstrated a 60% reduction in direct energy costs per ton-kilometer hauled compared to diesel trucks. Upward speeds increased by 10–15%, while downhill regenerative braking supplied up to 15% of the energy required for the subsequent haul cycle.

5. RESULTS AND DISCUSSION

The comparative synthesis confirms that battery electric mining equipment provides substantial long-term environmental and financial advantages over traditional diesel machinery. Key findings include:

1. Complete elimination of direct Scope 1 operational greenhouse gas emissions and hazardous underground diesel particulate matter.
2. Substantial reductions in underground ventilation and cooling demands, yielding energy savings on primary fan operations.
3. Lower overall operating expenditures (OpEx) driven by reduced energy costs and simplified drivetrain maintenance.
4. Enhanced occupational health and safety conditions resulting from reduced noise, lower ambient heat, and cleaner subterranean air (Hooli & Halim, 2025).

Although higher initial capital expenditure (CapEx) and charging infrastructure constraints present short-term implementation barriers, the operational cost savings and health benefits generate a compelling total cost of ownership (TCO) advantage over multi-year operational horizons.

6. CONCLUSION

Battery electric mining equipment represents a transformative technological advancement toward net-zero, environmentally responsible mining. This study demonstrates that electrifying LHD loaders, haul trucks, and drill rigs significantly cuts site carbon intensity, drastically lowers ventilation power demands, and reduces long-term operational costs. As battery chemistries advance and charging infrastructure matures, fleet electrification will serve as an essential driver for achieving global mine decarbonization and sustainable resource extraction goals.

7. RECOMMENDATIONS

1. **Adopt Phased Fleet Electrification:** Mining companies should implement a phased transition strategy, initially replacing high-duty underground LHDs before scaling to full haul fleets.
2. **Invest in Robust Charging Infrastructure:** Mine planning must incorporate fast-charging and battery-swapping infrastructure early in the mine design phase.
3. **Integrate Renewable Power Supplies:** Pair electric mining fleets with on-site renewable energy generation (solar, wind) to maximize life-cycle carbon reduction.
4. **Conduct Pilot Demonstrations:** Execute site-specific pilot projects to establish baseline operational metrics, operator training programs, and risk management protocols.

   Support Advanced Battery Research: Partner with OEMs and academic institutions to evaluate novel battery chemistries with enhanced thermal safety and higher power density.

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