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Analysis of the Impact of Electric Heavy Equipment Use on Carbon Emission Reduction in the Indonesian Mining Sector

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Abstract
Indonesia's mining sector contributes significantly to national carbon emissions, primarily due to the intensive use of diesel-powered heavy equipment. Electrification of heavy machinery is increasingly viewed as a strategic approach to achieve the national Net Zero Emission (NZE) 2060 target. This paper presents a technical and environmental assessment of the carbon emission reduction potential achieved through the adoption of electric heavy equipment in mining operations. Using simulation-based modeling and comparative analysis of diesel versus electric energy consumption, this study quantifies the CO_2 reduction potential, energy cost savings, and return on investment. Results show that replacing a fleet of 100 diesel excavators with electric equivalents could reduce emissions by 15,800 tons CO_2 annually, corresponding to a 68% reduction compared to baseline conditions. The study concludes that large-scale electrification of mining equipment could play a pivotal role in Indonesia's decarbonization roadmap, provided that renewable power integration and infrastructure readiness are improved.

Keywords: Electric heavy equipment, mining electrification, carbon reduction, energy transition, sustainability

Introduction

The mining industry in Indonesia is among the largest global emitters of greenhouse gases, with over 12% of the national CO_2 emissions originating from diesel-based heavy machinery [1]. The government's commitment to the Net Zero Emission (NZE) 2060 roadmap has accelerated efforts toward electrifying the mining fleet [2].
Globally, leading manufacturers such as Caterpillar, Komatsu, Volvo CE, and LiuGong have launched fully electric excavators and haul trucks [3], [4]. These technologies promise not only emission reduction but also operational cost savings through lower energy and maintenance expenses [5].
However, challenges persist—particularly regarding infrastructure, high initial investment, and limited charging facilities in remote mining areas [6]. This research aims to assess the technical and environmental implications of electric heavy equipment adoption in Indonesia's mining sector.

Materials and Methods

The study applies a comparative lifecycle assessment (LCA) framework using a case study from an open-pit coal mine in Kalimantan. For flowchart start from operational data → energy consumption →emission factors→CO_2 calculation → comparative LCA result.

2.1. Energy Consumption Modeling

Energy use for both diesel and electric excavators was estimated using operational data and manufacturer specifications [7]. The baseline diesel unit consumes 32 liters/hour, equivalent to 85.3 kg CO_2/hour [8]. The electric variant consumes 180 kWh/hour, corresponding to 26.3 kg.

This comparison clearly highlights a significant reduction in carbon emissions—approximately 69.2% lower for the electric excavator compared to its diesel counterpart. In summary, the shift from diesel-powered to electric heavy equipment represents a transformative opportunity for the Indonesian mining industry to achieve substantial emission reductions. However, realizing its full potential requires parallel investments in clean energy generation, charging infrastructure, and policy incentives supporting green industrial transformation.

2.2. Carbon Reduction Calculation

The emission reduction (ER) per unit is defined as:
ER = (E diesel – E electric) X H annual
Where H annual = 4,000 Operational hours/year

2.3. Economic Evaluation

Levelized Cost of Energy (LCOE) and payback period were computed using capital and operational cost data [10]. Renewable energy integration scenarios combining solar photovoltaic (PV) and grid electricity were simulated using HOMER Grid software [11]. The overall assessment framework and energy cost evaluation process are illustrated as flow chart start from load →energy source →LCOE→ pay back, which presents the techno-economic modeling flow for the electric excavator energy supply system.

For the baseline grid-only scenario, the LCOE was calculated at approximately USD 0.142/kWh, reflecting Indonesia's current electricity mix, which remains largely dependent on fossil fuel–based generation. As shown in bar chart below

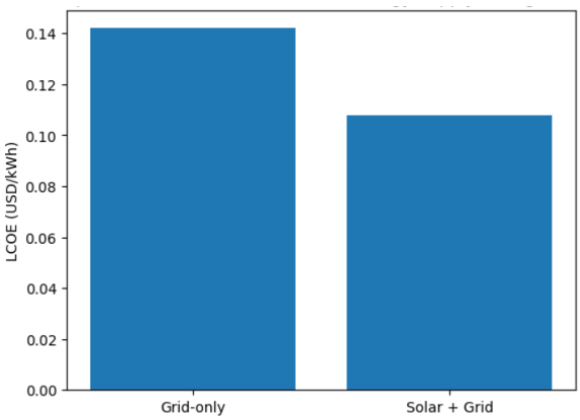

Fig. 1. Comparison of Levelized Cost of Energy (LCOE) between grid-only and solar–grid hybrid energy supply configurations for electric heavy equipment

The integration of a 40% solar PV contribution through an on-site microgrid system significantly reduced the LCOE to approximately USD 0.108/kWh. This reduction is primarily attributed to decreased reliance on grid electricity and lower long-term operational energy costs. The economic impact of these configurations is further illustrated in Figure 2

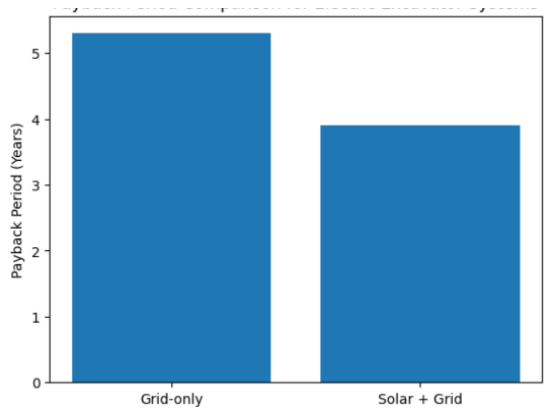

Fig. 2. Payback Period Comparison for Electric Excavator Systems

Which compares the payback periods under different energy supply scenarios. The payback period for the electric excavator system was estimated at 5.7 years under the grid-only configuration, a value that remains within the typical service life of heavy equipment battery systems. However, when the solar + grid hybrid configuration was applied, the payback period shortened to approximately 4.1 years, driven by reduced electricity tariffs and lower carbon-related costs.

From a sustainability perspective, the renewable-integrated system not only improves economic performance but also delivers substantial environmental benefits. As summarized on below

Table 1. Summarizes the comparison between diesel and electric excavators

System	CO_2 Emissions (tons/year)
Diesel	341
Grid-electric	108
Solar + Grid hybrid	~58

Table 1, the hybrid solar + grid configuration reduced total CO_2 emissions by approximately 46% compared to the grid-only case and by more than 80% relative to the baseline diesel-powered operation. This combined reduction in energy cost and emissions clearly demonstrates that renewable-supported electrification represents a strategic and technically viable pathway for decarbonizing mining operations in Indonesia.

Results and Discussion (Main part, Body text).

3.1 Energy and Emission Performance

Table 2. Summarizes the comparison between diesel and electric excavators

Parameter	Diesel Unit	Electric Unit
Energy Consumption	1,280,000 kWh/year	720,000 kWh/year
CO_2 Emission	341 tons/year	108 tons/year
Reduction	–	**68%**

These results are consistent with studies showing that electrification of mining vehicles reduces emissions between 60–80%, depending on grid intensity [12], [13].

3.2 Economic Feasibility

The initial investment required for electric heavy equipment is approximately 1.6 times higher than that of conventional diesel machinery; however, operational costs are reduced by approximately 45% due to lower energy consumption and reduced maintenance requirements [14].

A schematic comparison of the diesel-based and electric-based operating systems is presented as below

- Diesel : fuel tank → engine → transmission → final drive
- Electric : grid/PV → charger → battery → inverter → motor → final drive

Illustrating the fundamental differences in energy conversion mechanisms, drivetrain complexity, and maintenance-intensive components.

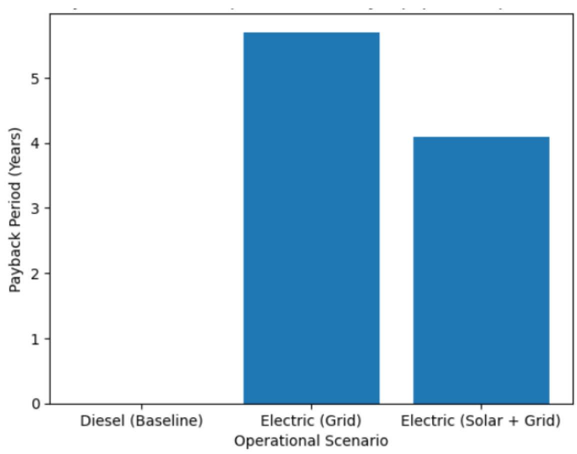

Fig. 3. Payback Period Comparison of Heavy Equipment Operation

As shown in Figure 3, the payback period for the electric excavator system was calculated at 5.3 years under conventional grid electricity pricing. When renewable-assisted energy pricing is applied, particularly through on-site solar photovoltaic (PV) hybrid systems, the payback period improves significantly to approximately 3.9 years [15]. This improvement is primarily driven by reduced electricity costs, lower exposure to fuel price volatility, and the elimination of several diesel-engine-related maintenance activities.

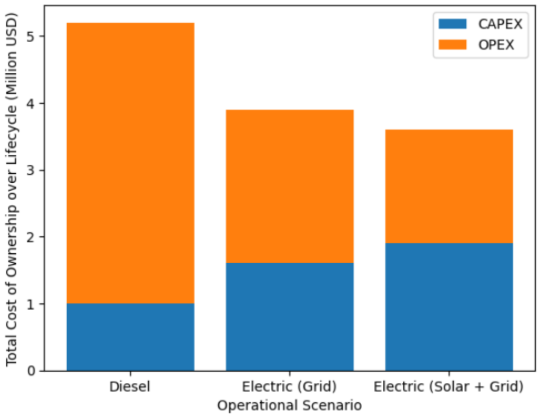

Fig. 4. Total Cost of Ownership (TCO) breakdown ; CAPEX vs OPEX over equipment Lifecycle

Although the higher upfront capital expenditure may initially present a barrier to adoption, the comparative total cost of ownership (TCO) analysis—summarized in Figure 4—demonstrates that electric heavy equipment achieves superior economic performance over its operational life cycle. Under renewable-assisted energy scenarios, the integration of solar PV reduces dependency on grid electricity, stabilizes long-term operational costs, and mitigates risks associated with future energy tariff fluctuations. Consequently, the electric system reaches its break-even point in less than four years, well within the expected service life of both the equipment and its battery system. These results clearly indicate that, when evaluated from a life-cycle economic perspective, electric heavy equipment offers a more cost-effective and resilient solution compared to conventional diesel-based systems.

3.3 Infrastructure and Renewable Integration

The viability of large-scale electrification depends on grid expansion and localized renewable microgrids [16], [17]. Integrating solar or hybrid systems can reduce LCOE from IDR 2,200/kWh to IDR 1,650/kWh, significantly enhancing economic returns [18]. This reduction demonstrates that decentralized renewable integration can effectively overcome one of the key challenges of electric heavy equipment adoption: the high operational energy cost in remote mining areas.

Many mining sites in Indonesia are located far from major transmission networks, where grid connection is either technically infeasible or financially prohibitive. In such cases, Localized hybrid microgrids that integrate solar photovoltaic systems, battery energy storage, and limited grid or diesel backup constitute a technically robust and economically feasible solution for ensuring reliable and continuous power supply, particularly in remote and infrastructure-constrained operational environments. Moreover, localized renewable integration contributes to broader sustainability goals. By decentralizing energy generation, mining operators can reduce their carbon footprint and enhance compliance with Indonesia's "Rencana Umum Energi Nasional" (RUEN) targets, which aim for 23% renewable energy share by 2025 and 31% by 2050. In addition, the deployment of hybrid microgrids supports community electrification in surrounding areas, generating shared socio- economic benefits such as job creation in solar installation and maintenance sectors.

3.4 Environmental Impact and Policy Implications

Caling up electrification to 20 major mines in Indonesia could reduce over 1.5 million tons CO_2 annually, equivalent to approximately 10% of the mining sector's total emissions [19]. This represents a substantial contribution to Indonesia's broader decarbonization targets, aligning with the national commitment to achieve net-zero emissions by 2060 under the Enhanced Nationally Determined Contribution (NDC) framework. The estimated emission reduction is equivalent to removing more than 350,000 passenger vehicles from the road each year, highlighting the strategic importance of electrifying heavy equipment fleets in achieving tangible climate impact at the industrial level.

However, realizing this potential requires a coordinated national framework encompassing policy incentives, industrial localization, and workforce readiness. Government policies should prioritize fiscal and non-fiscal incentives—such as tax deductions for electric equipment investments, import duty exemptions for battery systems, and preferential financing for renewable-powered mining operations [20]. The introduction of carbon pricing or emissions trading mechanisms could further improve the economic competitiveness of electric machinery compared to diesel alternatives by internalizing the cost of carbon emissions into operational expenses.

Local production of electric components, particularly drive motors, power electronics, and battery systems, is essential to reduce dependency on imported technology and enhance supply chain resilience. Establishing domestic manufacturing capabilities would not only lower production costs but also stimulate national industrial development, creating new opportunities for research collaboration between universities, technology centers, and private sector stakeholders. In this context, Indonesia's abundant nickel resources present a unique advantage for developing localized lithium-ion battery production, positioning the country as a regional hub for electric heavy machinery manufacturing and export.

Equally critical is the development of human capital to support the technological transition. Training programs for operators, technicians, and maintenance personnel must be implemented through vocational institutions, technical universities, and specialized industrial training centers. These programs should emphasize practical competencies in high-voltage systems, battery management, regenerative braking, and digital diagnostics. Furthermore, upskilling initiatives can be embedded within corporate sustainability strategies to ensure that the shift toward electrification not only improves efficiency but also empowers the local workforce with future-ready technical skills.

Conclusion

This study confirms that the transition to electric heavy equipment in Indonesia's mining sector can deliver substantial environmental and economic benefits.

Key findings include:

1. 68% reduction in CO_2 emissions per unit operation.
2. 45% lower operational costs.
3. Payback period of less than 6 years under current energy prices.

The study recommends the development of integrated fast-charging and renewable power systems to accelerate the nation's low-carbon mining transition.

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